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GENERAL REPORT ON WEAPONS TESTS

PRELIMINARY HYDRODYNAMIC YIELDS OF NUCLEAR WEAPONS

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March 2, 2001

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The Defense Threat Reduction Agency Security Office has performed a classification/distribution statement review of the following documents. The documents should be changed to read as follows:

WT-1628, AD-357954, OPERATION HARDTACK, PROJECT 3.4, LOADING AND RESPONSE OF SURFACE-SHIP HULL STRUCTURES FROM UNDERWATER BURSTS, UNCLASSIFIED, DISTRIUBTION STATEMENT A.

WT-1301, AD-341065, OPERATION REDWING, PROJECT 1.1, GROUND SURFACE AIR BLAST PRESSURE VERSUS DISTANCE, UNCLASSIFIED, DISTRIBUTION STATEMENT A.

WT-748, OPERATION UPSHOT KNOTHOLE, PROJECT 5.1, ATOMIC WEAPON EFFECTS ON AD TYPE AIRCRAFT IN FLIGHT. UNCLASSIFIED, DISTRIBUTION STATEMENT A. FORWARD TO YOU FOR YOUR COLLECTION

WT-9001-SAN, GENERAL REPORT ON WEAPONS TESTS, UNCLASSIFIED, DISTRIBUTION STATEMENT A. FORWARD TO YOU FOR YOUR COLLECTION.

POR-2260-SAN, OPERATION SUN BEAM, SHOTS LITTLE FELLER 1 AND 2, PROJECT 1.1, AIRBLAST PHENOMENA FROM SMALL YIELD DEVICES, SANITIZED VERSION. UNCLASSIFIED, DISTRIBUTION STATEMENT A. FORWARD TO YOU FOR YOUR COLLECTION.

If you have any questions, please call me at 703-325-1034.

Ardith Jarrett

ARDITH JARRETT
Chief, Technical Resource Center

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WT-9001 (SAN)

This document consists of 69 pages

No. 16 of 110 copies, Series A

PRELIMINARY HYDRODYNAMIC YIELDS OF NUCLEAR WEAPONS

By

Francis B. Porzel

and

Personnel of Group J-10

Los Alamos Scientific Laboratory
Los Alamos, New Mexico

December 1953

[redacted]

[redacted] document contains restric[redacted]a as de- fi[redacted]ic En[redacted]f 1946. Its transmittal [redacted]re of its contents in any [redacted] unautho[redacted]-

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ABSTRACT AND SUMMARY OF YIELDS

The analytic solution, as derived by the author, is an absolute method for the determination of the total hydrodynamic yield of a nuclear explosion from a measurement of the rate of growth of a strong shock. The diameter vs time of the shock front is measured, and the analysis for yield includes the first and second logarithmic derivatives of radius with respect to time; the method does not use the similarity assumption but assumes the presence of radiative transport, departures from the ideal gas laws, and a mass effect from the bomb and surrounding material.

The yields of all past test bombs, with the exception of Bikini-Baker and Jangle-Underground, have been evaluated in this manner in what is considered a preliminary way and are presented here in assembled form for the first time for distribution outside Los Alamos Scientific Laboratory. They are intended to supersede all previous fireball yields. Somewhat higher absolute yields are expected and were so obtained, on the average, with the analytic solution in comparison with previous radiochemical results. It is not expected that improved or standardized procedures will substantially change the hydrodynamic yields as a result of further study, but, if results here are not used as primary yields, they at least indicate that, in those cases where discrepancies are observed, diagnosis of the weapon or the interpretation of effects should be regarded as uncertain to the extent indicated by the difference between the radiochemical and hydrodynamic yields. A summary of the analytic-solution and radiochemical yields is given in the following table:

SUMMARY OF YIELDS

Bomb	Analytic solution, Kt	Radiochemistry, Kt
Trinity	27.2	17.4; 19.3; 23.8
Bikini-Able	25	19.6 to 22
Sandstone:		
X-ray	36	36.5
Yoke	50	48.7
Zebra	20	18.2
Ranger:		
A	2	1.27
B-1	6.9	7.83
B-2	7.4	7.95
E	Not quoted	1.00
F	21.7	22.2
Greenhouse:		
Dog	82.3	82.9
Easy	47.0	46.7
George	250	214.5
Item	45.7	45.7

[redacted]

SUMMARY OF YIELDS (Continued)

Bomb	Analytic solution, Kt	Radiochemistry, Kt
Buster:		
Baker	3.9	3.49
Charlie	13.8	14.0
Dog	20.3	21.0
Easy	30.3	31.4
Jangle-Surface	1.9	1.19
Tumbler-Snapper:		
Tumbler 1	1.45	1.055
Tumbler 2	1.45	1.167
Tumbler 3	28.5	30.7
Tumbler 4	19.7	19.2
(Snapper 1)		
Snapper 2	13.0	12.0
Snapper 3	12.0	11.1
Snapper 4	17.0	14.6
Snapper 5	Not quoted	13.9
Ivy:		
Mike	10.4 Mt	6 to 10.5 Mt
King	550	540
Upshot-Knothole:		
[redacted]	17.8	16.5
[redacted]	24.2	24.2
[redacted]	0.18	0.22
[redacted]	10.8	<11.3
[redacted]	0.30	0.21
[redacted]	27.4	23.0
[redacted]	51.5	41.8
Effects	25.9	26.0
[redacted]	32.4	27.2
Gun	15.5	14.9
[redacted]	60	60.8

[redacted]

ACKNOWLEDGMENTS

The results reported here were a principal part of the work of Group J-10 during a good part of 1953, under the direction of the author and Daniel F. Seacord, Jr., the assistant group leader, who was also the coauthor of a number of the reports. The members of the group who participated directly in the work on these reports were:

Thomas J. Andrews, Lt Col, USAF
Pedro R. FlorCruz, Lt Col, USA
E. Graydon Snyder
Jane R. Spack
Nancy M. Waddell

Background work and early calculations were carried on intermittently for a number of years, during which time the principal assistance to the author was given by two former members of the group: William D. Baker, CDR, USN, and Robert W. Newman.

It is also a pleasure to acknowledge the splendid cooperation of the members of Edgerton, Germeshausen & Grier, particularly Herbert Grier, Lewis Fussell, and Benjamin Brettler. Nearly all the analyses are based on film measurements made by them from their records.

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TABLES (Continued)

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CHAPTER 1

INTRODUCTION AND DISCUSSION OF RESULTS

1.1 PURPOSE

The purpose of this report is to present the results of the analytic solution for hydrodynamic yields on test bombs for past operations.

Although these results are generally considered preliminary in the sense that subsequent improvements in both the data and the techniques for analyses are expected as a result of further study, the results given here are considered of sufficient accuracy, utility, and importance to warrant a report at this time.

1.2 ORGANIZATION OF THE REPORT

This report is essentially a reprint of a number of J-Division documents concerning each separate operation.

Each report contains a preliminary discussion which suggests the reasons why, and the extent to which, the data are considered preliminary. A short discussion is then given for each bomb, and at the end of each report a tabulated summary is given of pertinent variables from the analytic solution. The details of the analyses are much too lengthy to be included here, and the basic data are contained in portfolios for each bomb, on file at Group J-10 at the Los Alamos Scientific Laboratory (LASL). Each portfolio contains three main sheets on which pertinent calculations are made and from which the final results are summarized. In addition, they contain the tabulation of the raw data as measured by Edgerton, Germeshausen & Grier (EG&G) and a number of graphs which are intrinsic in techniques to the solution itself.

The reports are given here in the chronological order in which they were written. The report for Operation Upshot-Knothole contains some discussion regarding the history of the problem and the equations used in the analytic solution; it should logically be read first. The report on Operation Ivy contains a short discussion of fireball perturbations, which is pertinent to all bombs but particularly to large-yield surface shots; it summarizes the principal results of studies over a number of years by the author.

The J-Division reports reprinted here as separate chapters are as follows:

Operation	Document	Date
Upshot-Knothole	J-20047	July 1, 1953
Ivy	J-20651	Aug. 1, 1953
Tumbler-Snapper	J-20636	Sept. 1, 1953
Greenhouse	J-20652	Oct. 1, 1953
Buster-Jangle	J-21669	Nov. 20, 1953
Ranger	J-21668	Nov. 23, 1953
Trinity, Bikini, Sandstone	J-22481	Dec. 15, 1953

In most cases these reports were preceded by reports on individual bombs, for which the more important documents and dates are listed in the following table. The most detailed discussion of the results is given in these papers, which are internal LASL documents.

Operation	Document	Date
Ivy-Mike	JF-1192	Nov. 1, 1952
	JF-1241	Nov. 5, 1952
	J-15470	Jan. 9, 1953
	J-16500	Mar. 9, 1953
Ivy-King	J-15470	Jan. 9, 1953
	J-16500	Mar. 9, 1953
	J-17754	May 15, 1953
IBM Problem M	J-17776	May 17, 1953
Upshot-Knothole:		
[redacted]	J-17158	Mar. 23, 1953
	J-17223	Mar. 31, 1953
	J-17258	Apr. 4, 1953
	J-17485	Apr. 20, 1953
	J-17292	Apr. 10, 1953
	J-16978	Apr. 27, 1953
	J-17348	Apr. 16, 1953
	J-17485	Apr. 20, 1953
	J-17414	Apr. 24, 1953
	J-17460	Apr. 30, 1953
Effects	J-17744	May 14, 1953
[redacted]	J-17819	May 18, 1953
	J-17840	May 24, 1953
Gun	J-17841	May 25, 1953
[redacted]	J-17845	May 27, 1953
	J-18331	June 9, 1953

Background material is contained in a number of other papers by the author, which are listed below. All except Report LA-1214 and the AFSWP Tumbler Report are internal laboratory documents.

Document	Title	Date
LA-1214	Rate of Growth of Atomic Fireballs	February 1951
J-8813	Notes on Early Fireball Growth for 0.2 Kt	Oct. 1, 1951
LADC-1133	Hydrodynamics of Strong Shocks	September 1951
AFSWP Tumbler Report, Annex XV	Free-air Pressure from Fireball Measurements	May 15, 1952
J-16455	Procedure for Analytic Solution on Fireball Growth	Mar. 4, 1953
J-16170	Scaling of Thermal and Blast Energy	Feb. 11, 1953
J-20337	Some Hydrodynamic Aspects of Thermal Radiation from Atomic Weapons	Sept. 23, 1953
J-20798	Some Hydrodynamic Aspects of Thermal Radiation from Atomic Weapons	Oct. 14, 1953

Report LA-1214 is a definitive paper which first resolved the then existing anomaly that the observed slope of a log radius vs log time plot was not constant at a value 0.4, as expected from previous theory. It was concerned principally with the discussion on variable gamma in

[redacted]

the equation of state and with radiative transport. Notes on the mass effect are contained in Report J-8813. The work on the equation of state for variable gamma was done a year or more prior to its publication in a series of graphs listed as Report LADC-1133. The Armed Forces Special Weapons Project (AFSWP) Tumbler report contains some discussion of the failures of scaling and is concerned principally with scaling yields for the Tumbler weapons. Report J-16455 is presently outdated because the calculation of the factor F was subsequently improved and standardized with the inclusion of second-derivative terms, as outlined in Chap. 2 of this report and in Reports J-17776 and J-17845, but the discussions concerning plotting and calculating are intrinsic to the high accuracy required for yield determination. No attempt should be made to apply the analytic solution to data which have been "fitted" with arbitrary or elementary assumptions, such as constant power laws for radius-time or pressure-distance. The discussion of thermal radiation in Reports J-16170, J-20337, and J-20798 is relevant to the question of energy partition and total hydrodynamic yields.

1.3 DISCUSSION OF RESULTS

An examination of the summarized results shows that the difference between the radiochemical yield and the hydrodynamic yield from the analytic solution is considered significant in approximately 13 out of the 40 bombs investigated. It is not the purpose of this report to resolve these discrepancies in detail, but the following discussion is pertinent.

It should first be noted that there is no fundamental reason why the total hydrodynamic yield should necessarily be identical with the radiochemical yield. The analytic solution evaluates the energy at a relatively late time on the basis of the apparent hydrodynamic energy without regard to the source or mode of production of the energy. On the other hand, the radiochemical yield is necessarily restricted to the calculation of energy release of known nuclear reactions. Whatever unknown mechanisms are present for the production of energy or in the conversion of nuclear or thermal radiation into hydrodynamic energy will be manifested as an increase in hydrodynamic yield over the radiochemical yield. This means that, for most diagnostic purposes, the radiochemical yield is properly applicable. On the other hand, even in the event of a real difference between the hydrodynamic yield and the energy calculated from radiochemistry, the analytic-solution or hydrodynamic yield is more suitable for the interpretation of most effects data if the fireball results are not otherwise suspect.

It should also be noted that such discrepancies do not involve questions of "partition of energy." By convention, the radiochemical yield is based on fixed, and somewhat arbitrary, values for "energy per fission" released up to an arbitrary time on the order of several milliseconds; it does not include the energy subsequently released, such as nuclear radiation in the decay of fission products. The analytic solution purports to evaluate the total hydrodynamic energy present, at times usually up to breakaway. The question of partition involves principally the fraction of thermal radiation emitted prior to breakaway, which was originally estimated as approximately 1 per cent by J. L. Magee and more recently by Group J-10 as being on the order of a few tenths of one per cent, depending on the size of the bomb and only for the usual ambient atmospheric conditions. To this extent, radiochemistry and the analytic solution are effectively on a common basis. In fact the usual agreement between the two absolute methods is amazing and satisfying; radiochemistry is based on measured and calculated values from nuclear reactions, whereas the comparable basis of the analytic solution is in the completely different realm of the chemical composition of air.

The accuracy on some yields, especially Upshot-Knothole, was quoted as a flat ±10 per cent, more by way of reasonable caution in the application of a preliminary number than an actual indicated uncertainty. The relative uncertainties from bomb to bomb are, in general, better judged from the statistical deviation as given in the tabulated results for each bomb. These fluctuations are inherently due, in good part, to the inability to resolve the first and second derivatives with the desired precision; however, by the techniques employed the average values of these quantities should be correct even though minor fluctuations in calculated yield will occur at different periods in the growth of the bomb. The statistical deviation should be re-

garded as a minimum uncertainty because it does not include constant errors in the data, in the form of the solution, or in the equation of state. In general, on operations other than Upshot-Knothole the attempt has been made to estimate this uncertainty as part of the recommended preliminary hydrodynamic yield, from the quality and number of films, location of cameras, and internal consistency between Rapatronic and Eastman cameras.

An intrinsic part of the analytic solution is the denial of the validity of similarity scaling for strong shocks which, in turn, is based on considerations of radiative transport, mass effect, and variable gamma in the equation of state. As predicted in Report LA-121[redacted] the early slopes should be approximately 0.1 out to pressures on the order of 80,000 atm or a Mach number of 250 for the shock. This has been amply verified[redacted] The consideration[redacted] in Report J-8813 predicted that the initial slopes should be more on the order of 1.0[redacted] this was repeatedly verified on all bombs[redacted] Thereafter the time history of the slope varies from bomb to bomb, and, although slopes become comparable between bombs at late times, there is never a region in one bomb in which the slope n can be regarded as constant, let alone in a comparison between bombs.

Some remarks are appropriate about the equation of state in Report LADC-1133. The bulk of this work was done by the author and members of his group as early as 1949, primarily as a hydrodynamic study, and at that time the theoretical equation of state was expected to be no better than about 20 per cent in the regions of interest. With the development of the analytic solution and its success on a number of bombs, it was hoped, particularly on Operation Upshot-Knothole, that, by combinations of theoretical and empirical methods, it would be possible to improve the equation of state beyond the accuracy of the values given in Report LADC-1133. It is important to note that no substantial improvement could be made by pegging to empirical data, and at present the average values of the theoretical equation of state, over the range of interest, are apparently accurate to the order of a few per cent. The yield is insensitive to the equation of state because of terms like $(\eta_s-1)/\eta_s$ and similar insensitive terms in the analytic solution at the shock front. At the same time, the yield is roughly proportional to $\bar{\epsilon}$, but ϵ appears only as an average value on the interior, and it is expected that increased accuracy will be obtained by virtue of the integration performed in obtaining this average value. The average value of $\bar{\epsilon}$ varies theoretically from values on the order of 4.0 at 10^4 atm to a maximum of 5.6 near 300 atm, eventually dropping to 2.5 at low pressures. The analytic solution has been applied on one bomb or another from pressures on the order of 3 atm to well above 20,000 atm. Despite the variation of a factor of 2 in $\bar{\epsilon}$, the internal consistency of the yield is good assurance that the value of $\bar{\epsilon}$ is reasonably correct at high pressures because of the certainty with which it is known at low pressures such as 3 atm.

It is not the purpose of this report to evaluate the discrepancies between radiochemistry and the analytic solution, but it is worth while to note that subsidiary methods generally give results which are almost always (thermal data on Tumbler 1 and 2 appear to be exceptions) in better agreement with the analytic solution than with radiochemistry and often are on the far side of the analytic solution from radiochemistry. These methods include total thermal-radiation, bhangmeter, time-of-arrival, and pressure data. Recently the gamma-ray analysis by John S. Malik of LASL has also shown these high yields of the Ranger A type bombs.

Where discrepancies exist on fission yields, there usually seems to be reasonable doubt of fireball data or sampling on radiochemistry. Trinity radiochemical results were based on ground samples, and it is understood that no great reliability is attached to them. The hydrodynamic yield on Bikini-Able has been obtained from a single-streak camera record, and the discrepancy could be within experimental error.[redacted] and slow cameras restrict the range of reliable fireball analysis. On the other hand, they were either surface shots, or, because of small size, they scale to a very high airdrop; according to Harold F. Plank of LASL fractionation is expected in either case. No hydrodynamic yields have been quoted for Ranger E because of the restrictions cited for the Ranger A bombs. On Tumbler 3 it is believed that fractionation of the radiochemical samples is now recognized. The discrepancy on Tumbler 7 is not understood because it was a tower shot of the same general size in

[redacted]

which the agreement between the hydrodynamic yield and radiochemistry is usually good. No hydrodynamic yield is quoted on Tumbler 8 because of the gross asymmetries in the fireball pictures which made it impossible to quote a reliable yield. The substantial majority of fission weapons is in reasonable agreement.

The thermonuclear devices present a different aspect in which the hydrodynamic yields are usually 17 to 22 per cent higher than the radiochemical yields. This is a long-standing discrepancy, first observed on George, but at a time when the fireball method was restricted to similarity scaling and was reasonably discredited in comparison with radiochemistry. The excellent agreement between radiochemistry and the analytic solution on the other bombs of the Greenhouse series and the good quality of the George films at late times leave little reason to discredit the hydrodynamic yield on George, and the difference of 17 per cent is probably real. The discrepancy on Ivy-Mike is well known, and originally radiochemistry was more than a factor of 2 lower than the hydrodynamic yield. The present analytic-solution yield differs only by 6 per cent from changes in fireball data analyzed the day of the shot. This discrepancy on Mike was later attributed to uranium contamination from the soil in the radiochemical samples, and at present there is no actual discrepancy because radiochemistry now indicates that a yield of 10.5 Mt is reasonable for Mike. There are further discrepancies on [redacted] (analytic solution 19 per cent higher) [redacted] (22 per cent higher), and [redacted] (19 per cent higher). Categorically then, the hydrodynamic yields are higher by some 17 to 22 per cen[redacted] with the exceptio[redacted] in which both methods fortuitously give a yield of 24.2 Kt.

Considering that both the analytic solution and radiochemistry are absolute methods, it would be expected that these discrepancies are partly due to a constant difference between methods. The present radiochemical yields are based on values for energy per fission which were estimated by Harris L. Mayer, Frederick Reines, and others at LASL around the time of Trinity and Sandstone. The author understands from R. W. Spence and F. Reines that subsequent laboratory experiments have raised these values about 10 per cent. Accordingly, all present radiochemical yields could appropriately be raised by this amount, but, for consistency with earlier yields and to avoid frequent changes in quoted yields as the energy per fission is revised, the radiochemical yields are presently calculated on the basis of the old values for energy per fission. It is of interest to note that a straight comparison of yields as tabulated in the Abstract gives an average ratio for 35 bombs by which the analytic-solution yield is actually 10 per cent higher than radiochemistry; in this compariso[redacted] were not counted because of radiochemical fractionation, and Mike was not counted because of the large initial uncertainty in radiochemistry. For reasons indicated previously the differences [redacted] If, [redacted] we eliminate [redacted] because of [redacted] and [redacted] because of the large uncertainty in the analytic solution, then the average ratio for 28 bombs is such that the analytic-solution yield is 9 per cent higher than radiochemistry. However, this is not considered conclusive confirmation of the 10 per cent difference on an absolute basis. We can further refrain from comparing all bombs prior to Greenhouse before Rapatronic cameras were used because of the uncertainty on zero times. Also, the discrepancy on [redacted] seems abnormally large and subject to some additional error (not presently clear). Eliminating these bombs from the comparison, in addition to those listed previously, there remain 16 fission weapons whose average hydrodynamic yield is about 4 per cent higher than radiochemistry: [redacted] In summary, we expect the radiochemical yields to be about 10 per cent low; the present comparisons with the analytic solution confirm a difference of at least 4 per cent, and possibly 10 per cent, in the proper direction.

For the reasons discussed above, and including the subsidiary measurements, the author feels some assurance in quoting these preliminary numbers, especially for effects purposes. It is clear that such discrepancies as do exist should be made the subject of serious study in the future for improvement of the analytic solution as well as for radiochemistry and the other subsidiary methods. For the present, perhaps the important point is that, in those cases where

[redacted]

discrepancies exist, reasonable caution should be exercised in diagnosing these weapons and in the interpretation of effects data. It is planned that the present series of bombs will be restudied, using a standardized procedure and improved techniques as discussed in the separate reports, particularly with regard to zero-time correction. Although it is not expected that the hydrodynamic yields will vary by substantial amounts as a result of further study, it is to be expected that some change will occur within the uncertainties quoted, and meanwhile reasonable and appropriate conservatism should be attached to the results given in this report as much as to the results obtained by radiochemistry.

[redacted]

CHAPTER 2

OPERATION UPSHOT-KNOTHOLE

By F. B. Porzel

July 1, 1953

2.1 HISTORY AND PURPOSE

The fireball method for yield determination consists in measuring the rate of growth of the shock front from a nuclear explosion by photographing it during the time it is luminescent, i.e., out to breakaway. A theory has been deduced using strong-shock hydrodynamics which gives the total hydrodynamic yield of the bomb in an analytic expression which involves the diameter vs time, together with its first and second derivatives, and a theoretical equation of state.

Early theory by T. B. Taylor, J. A. von Neumann, Hans Bethe, and K. Fuchs indicated that, as a result of the properties of strong shocks, the radius of a strong shock could be expressed as a function of time in the form

$$R \sim t^{0.4}$$

This was implied by the similarity-scaling property which assumed that peak pressure was related to the shock radius by

$$P \sim \frac{1}{R^3}$$

This property would permit accurate and simple scaling from a measurement of the fireball growth. Although the theory was apparently verified on Operation Trinity, more careful measurements at Operation Sandstone showed that the slope of the ln R vs ln t plot differed significantly from 0.4 and had, in fact, an average value of about 0.374.

In a number of later papers, principally Report LA-1214, this apparent anomaly was explained, and it was shown that the simple concepts used to deduce the 0.4 law did not apply because the hydrodynamic growth was strongly controlled by three phenomena:

1. Radiative transport: At sufficiently high temperatures appreciable energy is transported by radiation. At very early fireball times even the shock front propagates by radiation rather than by hydrodynamics. During times of interest the effect is to make the radius larger at a given time than it would have been by shock hydrodynamics alone. The slopes of the ln R vs ln t plot are more like 0.1 rather than 0.4 during early times for [redacted] The pressure falls off more rapidly than $1/R^3$.

2. Mass effect of the bomb: During the time that the mass of the bomb (plus the surrounding cab and tower) is not small compared with the mass of air engulfed by the shock, the hydrodynamics are again strongly perturbed. During these times the radii are generally smaller than they would have been from shock hydrodynamics alone, and the slope of the ln R vs ln t plot is more like 1.0 than like 0.4. The peak pressure is nearly constant for a short time.

3. Variations in equation, variable gamma: For strong shocks the equation of state of air is not sufficiently well approximated by the ideal gas law. This in itself results in a failure of the $P \sim 1/R^3$ law. These variations in the equation of state are available through calculations by J. O. Hirschfelder, C. F. Curtiss, and Hans Bethe and were correlated by a theory of variable gamma by Porzel in Report LADC-1133. Such variations in the equation of state of air result in differences of factors of 2 or 3 in the apparent energy of the bomb.

These perturbations strongly affect the fireball rate of growth as it is portrayed in the slope of the ln R vs ln t plot, which varies considerably from bomb to bomb, depending principally on the yield-to-mass ratio and, to a much smaller extent, on ambient conditions. In Report LA-1214 methods were suggested whereby it could be determined unambiguously whether or not the "fireball scaled" in the sense that, for bombs of two different yields, the distance at which a given hydrodynamic variable occurred (such as shock velocity or shock pressure) was always in the ratio of $W^{1/3}$. On Operations Buster and Tumbler this type of analysis showed, indeed, that this type of scaling could not be applied at high pressures. Resort was then made to an analytic expression for strong shock which had been derived by Porzel some years previously for studying the effect of these perturbations. It was applied with encouraging success to a number of bombs fired before Operation Ivy. An additional incentive for fundamental methods was occasioned because of the large change in scale for the weapons on Ivy. The analytic solution was used to determine the yields for these two bombs.

Several advantages are inherent in the analytic solution for the fireball method. It is an absolute yield in itself because the yield of each bomb so analyzed is obtained solely from hydrodynamics and a theoretical equation of state, without reference to any other bomb. A high degree of precision is afforded in the photographic method because of the multiple measurement of the entire shock front which is possible during these times. It is a measure of the total hydrodynamic yield, less only a small fraction of thermal and nuclear energy which escapes the fireball prior to the light minimum. It does not depend on the nuclear processes of fission or fusion assumed for release of the energy. In principle the variations can be seen in radiative transport from bomb to bomb; it will be a useful tool in such studies. Finally, validity of the yield is not destroyed by the ambient conditions of burst height from either very low or very high heights of burst.

During Operation Upshot-Knothole the analytic solution was, in part, considered a feasibility test which investigated the validity of the theory and the equation of state on bombs of vastly different yield-to-mass ratios and conditions of burst. As the operation progressed the consistency of the fireball yield, as determined from the analytic solution, lent sufficient creditability and verification that the role of the method passed from that of hydrodynamic study into the primary method for total yield on atomic weapons.

The fact that the hydrodynamic yield is independent of the nuclear processes is a limitation as well as an advantage. The details of the energy release are matters of radiochemistry, whereas the total energy is a matter of hydrodynamics.

2.2 METHOD

The detailed derivation for the analytic solution is too lengthy to be given here, but the final expression for the yield is given by

$$W = \rho_0 n^2 \frac{R^5}{t^2} F = \frac{\rho_0 n^2 \phi^5 F}{32}$$

[redacted]

where W = total hydrodynamic yield in tons

ρ_0 = ambient air density in grams per cubic centimeter

n = slope of the ln R vs ln t curve

R = radius of the shock front in meters

t = absolute time in milliseconds

$\phi = D/t^{2/5}$

D = diameter in meters

F = a numerical factor, defined below

ϕ is used simply for convenience because it is constant when n = 0.4 and is, in general, a slowly varying function. The factor F is complex; it represents the various integration constants arising from the integration of the total hydrodynamic energy within the blast wave, depending upon the shape of the interior wave as it is deduced from conditions at the shock front. The factor F is given, to an approximation of about 1 per cent, by the expression

$$F = \frac{\eta_s - 1}{\eta_s}\left[\bar{\epsilon}\,(1 - K) + \frac{3\bar{\epsilon}K}{q + 5} + \frac{3}{2}\,\frac{\eta_s - 1}{q + 5} + \frac{\bar{\epsilon} - \epsilon_0}{\xi_s - 1}\right]$$

In this expression η_s is the density compression ratio at the shock front, as derived from Report LADC-1133, ξ_s is the pressure ratio across the shock front, and $\bar{\epsilon}$ represents the average value of gamma on the interior of the fireball, where gamma is defined by the internal energy per unit volume, E_i, through

$$E_i = \frac{P}{\gamma - 1}$$

$$\epsilon = \frac{1}{\gamma - 1}$$

and $\bar{\epsilon}$ is defined by

$$\bar{\epsilon} = \frac{\int_0^R \epsilon P\, dv}{\int_0^R P\, dv}$$

Tabulated values of $\bar{\epsilon}$ were obtained using this definition, and typical wave forms were deduced both from the analytic solution and from a machine solution of the hydrodynamics at low pressures. All used the equation of state from Report LADC-1133. The variable gamma theory itself is the formulation of strong hydrodynamics, which is consistent with the fundamental definition above. K is a parameter in which 1 − K expresses the fraction of the pressure on the interior of the shock wave to the peak pressure at the shock front. It is given by

$$K = \frac{1}{q + 2}\left[\frac{\eta_s}{n}\left(1 - \frac{d \ln m}{d \ln t}\right) - (\eta_s - 1)\right]$$

q is a parameter which represents the average decay of density behind the shock and is calculated from

$$q = 3\left[\frac{\eta_s}{1 + (M/M')} - 1\right]$$

where M = mass of bomb, with surrounding cab and tower

M′ = mass of air engulfed by the shock

m = the slope of the mass-motion lines on the interior of the fireball = d ln r/d ln t

At the shock m is related to n by

$$m = \frac{\eta_s - 1}{\eta_s}\, n$$

$(\bar{\epsilon} - \epsilon_0)/(\xi_S - 1)$ is a correction arising in the derivation from subtracting the original hydrodynamic energy of the air before the explosion because the internal energy of the air engulfed by the shock has been altered by the equation of state.

An essential feature of the analytic solution is the use of slowly varying functions like n, ϕ, and F in the final expression for yield for "bookkeeping" advantages rather than expressing the yield in rapidly varying functions like pressure or shock velocity. Even then it is difficult to make experimental measurements of the fireball radius over a small time range with sufficient precision to determine n and (d ln m)/(d ln t) to the degree of accuracy desired. Nonetheless the computation involving m, n, and (d ln m)/(d ln t) is calculated in such a way that their average value is correct, i.e., the lowness of n at one time will be compensated for by a correspondingly higher value of n at some other time. This uncertainty results, of course, in minor fluctuations of the yield at these times, but the average value is bound to be nearly correct. It is later possible to reiterate the solution and keep W constant by smoothing the instantaneous value of n, m, and (d ln m)/(d ln t). The requirement is, however, to rigorously maintain the same average values after the reiteration and at the same time to carefully investigate whether the reiterated value for the diameter remains within the probable error of the mean as deduced statistically from the measurements themselves.

There is a simpler method of estimating the yield from fireball methods. This is "ϕ^5 scaling" derived and used by EG&G. The idea is to plot ϕ as a function of time until, as expected near breakaway, the slope n passes through 0.4 and ϕ becomes constant. The yield is then given by

$$W = \rho_0 C \phi^5$$

The constant C is empirically deduced from pegging to radiochemical results on a number of bombs from Operations Greenhouse, Ranger, and Buster. The ϕ^5 scaling furnishes a useful check on the fireball yield, despite its approximate nature, because it correlates the fireball yield with past radiochemistry results and is essentially independent of the hydrodynamics of the analytic solution. A more careful procedure should alter the value of the constant C, depending on the value of F for the time and pressure at which the slope n passes through 0.4, but this would still not include the variations in (d ln m)/(d ln t) or m, from bomb to bomb, at the time when n = 0.4.

2.3 RESULTS AND CONCLUSIONS

Tables 2.1 to 2.11 show the results of the analytic solution for each of the Operation Upshot-Knothole bombs. They also provide the data for constructing the time-of-arrival curve, shock velocity vs distance curve, and pressure-distance curve for each of the bombs. Upon examination of the tables it will be observed that the functions n^2, ϕ^5, and F all vary continuously and in different fashions from bomb to bomb, but for the most part the yield is essentially constant for a given bomb, with minor fluctuations for reasons given above. The failure of simple scaling for nuclear explosions during fireball growth is contained in the observation that, if simple scaling were correct, quantities n and F would be constant not only in time but from bomb to bomb; the quantity ϕ would always be constant for a given bomb.

The following comments are of interest on separate bombs:

[redacted] on Operation Upshot-Knothole is part of a logical sequence, which includes [redacted] of Operation Snapper and [redacted] of Operation Upshot [redacted] The firing conditions for [redacted] are similar from a hydrodynamic point of view; the yields are about the same, and shots were on 300-ft towers. The analytic-solution yields [redacted] are in substantial agreement with radiochemistry [redacted] The analytic solution has been obtained in a preliminary way for [redacted] and showed a yield of 16.9 Kt; [redacted] It is in excellent agreement with the ϕ^5 scaling value of 17.0 Kt but is considerably higher than the radiochemical value of 14 Kt. Although the fireball yield [redacted] is

still a "preliminary value" because only limited data and time were available for the analytic solution, the difference between it and radiochemistry is considered significant and probably leads to a different interpretation of the yield vs initiation time curves. [redacted] was a very high airdrop, but it is not believed that this affects the observed comparison that [redacted] at 10.8 Kt, is approximately 10.5 per cent below [redacted] No comparison with radiochemistry is available [redacted] because of fractionation of the radiochemical samples; according to H. Plank, fractionation can be expected on all high airdrops.

[redacted] are of interest in the analytic solution because of the large mass effects on each of them. [redacted] the accuracy of the fireball method is poor because of the large uncertainty of the mass of bomb and cab which participated in the hydrodynamics [redacted] The fact that the fireball yield is even in approximate agreement with radiochemistry for these two bombs is considerable justification for thinking that the essential ideas of the mass-effect correction in the analytic solution are valid. [redacted] have high mass and asymmetric effects because of the large concrete shield used on the cabs and towers. It will be observed that [redacted] is in essential agreement with radiochemistry, whereas the fireball on [redacted] is significantly higher (51.5 Kt as compared with approximately 44.5 Kt). In each case the mass of bomb and tower were about the same order, and this comparison with radiochemistry would indicate that there may be some fundamental unknown contributing to the total yield on [redacted] fireball was asymmetric as viewed from two different stations, each giving different rate-of-growth curves. The films from one station, analyzed separately, gave 51.8 Kt; the films from another station, analyzed separately, gave 51.2 Kt. This is some justification for the belief that, despite the differences in the radius-time curves between the two stations, the yield can be deduced by the analytic solution without being strongly affected by asymmetries.

The Effects shot, with a hydrodynamic yield of 25.9 Kt, is somewhat lower than may have been expected. However, the analytic solution was applied to its counterpart, [redacted] this showed that the hydrodynamic yield was 28.5 Kt for that weapon. This is a reduction below both the radiochemical value and $\dot{o}^5$ fireball scaling (approximately 30.5 Kt) reported at the time. The lower value, at least for the hydrodynamic yield, is believed correct because it is now believed some fractionation for radiochemistry may have occurred [redacted]

On several shots, [redacted] the fireball was analyzed separately from the Eastman and Rapatronic films. There are, at times, significant experimental differences between these two types of data, especially over the range of pressures encompassed by the analytic solution. [redacted] the agreement is excellent; satisfactory yield agreement was also obtained on the Gun, [redacted] On the other shots it is not always possible to obtain sufficient points or to rely on the Rapatronics alone to the extent of a separate analytic solution. An outstanding result of Operation Upshot-Knothole is the requirement for resolving the differences between the data obtained by these two different camera methods.

The Rapatronics extend to early times, [redacted] in particular, the data were sufficiently smooth to apparently give a dependable radius-time curve up to 18,000 atm. [redacted] it will be noted that the indicated yield at these high pressures is not markedly different from the average value over the entire range. This consistency is considerable reassurance that the theoretical equation of state, as used in the analytic solution from Report LADC-1133, is substantially correct. Although it is not reported in Tables 2.1 to 2.11, concurrent investigations were carried out which applied the analytic solution at pressures considerably below those measured in the fireball. One study was the application of the solution to IBM Problem M, which showed that the analytic solution (and the equation of state) were valid down to approximately 3 atm. On [redacted] a film was obtained by EG&G which permitted measurement of the shock front from breakaway out to radii corresponding to very low pressures. The analysis of a preliminary measurement on this single film indicated that the

yield [redacted] was 49 ± 4 Kt, which is in satisfactory agreement with the fireball determination as reported above and in Table 2.7. Naval Ordnance Laboratory (NOL) rocket data are available from some shots which should also provide a radius-time curve at low pressures. With these data preliminary investigations showed that the deduced yield is not sufficiently constant from high to low pressures; on two bombs the apparent yield rose at late times, and in the third case the bomb apparent yield fell at late times. This could be interpreted as failure of the analytic solution at low pressures, except for the reasonable agreement which has been obtained at these pressure levels on [redacted] as noted above. In addition, reasonable yields were deduced from similar analyses of LASL mass-motion data obtained on Mike and King shots during Operation Ivy.

In summary, it appears from Operation Upshot-Knothole that there are no serious difficulties with the analytic solution for total hydrodynamic yield with respect to the range of applicability of the solution, the equation of state for air, mass-effect corrections, or asymmetries. Although the accuracy is quoted as ±10 per cent for preliminary numbers, the accuracy is often indicated to be a few per cent. The study indicates that 1 per cent accuracy could be realized as standard practice if the method were exploited.

It seems that a requirement does exist to improve the accuracy of the measurements by whatever refinements are possible. In particular, the differences between the Eastman and Rapatronic data should be resolved, and, to a further extent, the discrepancy should be resolved between the radius-time curve as observed from the Control Point (CP) as compared with the radius-time curve observed at much closer stations in the field. At the present time it is hardly conceivable that both the analytic solution and the equation of state in it are accurate to the degree desired, but the fact remains that scatter of the present data does not provide sufficient resolution to improve either.

A requirement exists to extend the range of measurements for yield beyond breakaway, even though measurements may lack the high precision afforded by multiple measurements in the fireball region. This is done in order to study the hydrodynamic yield at lower pressures where the analytic solution is still applicable, but the asymmetries, due to mass effect, are considerably smaller, and the equation of state is more certain. The mass-motion technique is probably better suited to the analysis than the rocket-trail techniques for this purpose, but it may be possible to photograph the shock wave directly, as observed [redacted]

The analytic solution itself, as well as the theoretical equation of state used in it, must still be considered as continuing studies, anticipating more precise and a broader range of data. There is a particular requirement to study the equation of state for the solid materials in the bomb and cab as they affect the bomb of low yield-to-mass ratio.

2.4 TIME-OF-ARRIVAL METHOD FOR YIELD

2.4.1 Purpose

The time-of-arrival method on Operation Upshot-Knothole was an informal activity of Group J-10 to study the feasibility of using the time of arrival at long distances to obtain an absolute hydrodynamic yield. Such a yield is independent of radiochemistry, the analytic solution for fireball growth, or results from past operations. It is free from the nonscaling features of the blast wave as encountered during the fireball growth or shortly after. It represents an integrated effect of the blast wave at long ranges long after the pertubation due to the interaction of the ground surface with the blast wave. The method is rapid because it permits a determination of the yield only a few moments after the arrival of the shock wave.

2.4.2 Methods

The time-of-arrival measurement is in two steps: the determination of acoustic time and the determination of shock-arrival time. The time of arrival itself is much too insensitive at long ranges to furnish a reliable basis for estimating the yield; it is a much better estimate for ambient-sound velocity. There is, however, a small difference between the acoustic time

(the length of time required for a sound signal to travel from bomb to observer) and the shock-arrival time (the corresponding time for the actual blast wave). It is this small difference in time which is scaled from the theoretical blast curve by the cube-root scaling law. The method presupposes an extremely accurate theoretical time-of-arrival curve; this was obtained from the machine solution of the blast-wave hydrodynamic problem. The energy of the blast wave was evaluated by direct integration. For each bomb a graph is constructed which gives the time difference as a function of yield for a specific bomb-to-observer distance. This graph is constructed from the theoretical curve for 1 Kt, as follows: An arbitrary yield is assumed, the scaled distance for 1 Kt is calculated, and the time difference for 1 Kt is read and scaled back up to the arbitrary yield. From a number of such arbitrary yields, a Δt vs W curve can be drawn. Immediately upon shock arrival the time difference is obtained by subtracting the shock-arrival time from a previously calculated acoustic time, and the yield of the bomb is read directly from the Δt vs W plot.

The ambient-sound velocity was calculated for each shot from predictions by the Air Weather Service and was later checked by their measurement at shot time. In nearly all cases the agreement is excellent. This calculated sound velocity was further checked by a measurement during the previous night, using the arrival time from TNT charges by Sandia Corporation. Microbarograph readings for the TNT charges were not obtained in all cases; so the primary reliance has been on the calculated sound velocity.

The shock-arrival time was measured with stop watches, although it was recognized that the time resolution of this method was too poor to give yields accurate on the order of a few per cent. Where possible, the arrival times from the microbarograph of Sandia Corporation were used as a check on the reliability of the stop watches. Microbarograph times for the nuclear explosions were not obtained in all cases; so again the primary reliance has been on stop-watch measurements.

For high airdrops a correction for height of burst is applicable because of the difference in the pressure-distance curve to the distance at which the reflected wave becomes truly hemispherical. It is not clear that this correction is appreciable without further study of the shape of the height-of-burst curves for pressures below 2 psi.

2.4.3 Results

Table 2.12 summarizes the pertinent values obtained for each shot. All measurements of yield are in good agreement with the yield as determined by the analytic solution. The stop-watch technique cannot be expected to give yields much better than 20 per cent. The inherent accuracy in the time of arrival is about 0.2 sec; the uncertainty in the yield results from this 0.2 sec, as compared with the time difference, which is then cubed. The calculated and measured values of ambient-sound velocity were always in reasonable agreement, although not to the precision that would be desired. As often as not, the weather changed appreciably from the time of the last high explosive shot to the time of the nuclear shot; therefore the calculated values at burst time were probably just as reliable as the measured values an hour or two earlier.

The time uncertainty of the stop watch is, of course, too great for detailed judgments regarding the relative merits of different ways of obtaining the sound velocity or height-of-burst correction; for the most part the uncertainties in sound velocity and the correction for height of burst are lost in this time resolution.

The feasibility of the method is considered justifiable to the extent of expending some effort in the construction of simple time-of-arrival switches. Such a device can and should be operated independently of external power or timing signals; it might be a clock started by bomb light and stopped by the shock wave. It should have a resolution of approximately 0.01 sec for small bombs, although 0.1 sec would be sufficient for large bombs. By placing two or more such devices separated by a reasonable difference in radial distance from the bomb, the ambient-sound velocity could be determined precisely at shot time from comparisons in time of arrival; no great accuracy is required in the yield to correct for the difference between shock

velocity and sound velocity at long ranges. From two or more such devices both the ambient-sound velocity and the yield could be checked for internal consistency.

2.4.4 Conclusions

It is concluded that

1. The time-of-arrival method is feasible for the rapid determination of an absolute hydrodynamic yield, probably to an accuracy of a few per cent and certainly within an accuracy of 10 per cent.

2. The construction of time-of-arrival switches, as indicated above, would be justified for future operations.

Table 2.1—FIREBALL YIEL[redacted]UPSHOT-KNOTHOLE 1)

Analytic Solution

Data: EG&G Eastman films:
17001, 17002, 17003, 17004,
17005, 17006, 17007, 17008,
17014; plus 10 Rapatronics

Ambient conditions:
Pressure (P_0), 0.866 bar
Density (ρ_0), 1.074 g/liter
Sound velocity (C_0), 0.336 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.333	48.60	22.32	630	0.1289	0.1600	2.64	18.2
2.916	52.75	19.60	490	0.1318	0.1535	2.68	18.2
3.645	57.00	17.13	375	0.1347	0.1465	2.70	17.8
4.556	61.75	15.09	290	0.1391	0.1384	2.79	18.0
5.695	67.00	13.27	222	0.1429	0.1332	2.76	17.6
7.119	72.75	11.71	173	0.1475	0.1300	2.75	17.7
8.899	79.50	10.34	133	0.1505	0.1285	2.68	17.4
11.124	87.00	9.19	104	0.1552	0.1285	2.65	17.7
13.905	95.00	8.13	81	0.1592	0.1285	2.63	18.0
17.381	103.5	7.16	62	0.1624	0.1290	2.52	17.7
20.90	112.0	6.49	51	0.1648	0.1295	2.43	17.4
21.29	112.25	6.39	48.5	0.1648	0.1300	2.42	17.4

Av. (statistics only) 17.8 ± 0.1

ϕ^5 Scaling

ϕ = 66.25 W = 17.7 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 17.8 ± 1.8 Kt

Table 2.2—FIREBALL YIELD [redacted] UPSHOT-KNOTHOLE 2)*

Analytic Solution

Data: EG&G Eastman films:
17101, 17102, 17103,
17104, 17105, 17106,
17107, 17108

Ambient conditions:
Pressure (P_0), 0.860 bar
Density (ρ_0), 1.045 g/liter
Sound velocity (C_0), 0.3395 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
4.000	67.03	17.75	410	0.1291	0.2710	2.149	24.5
5.657	76.71	14.45	265	0.1305	0.2528	2.269	24.4
8.000	86.07	11.53	170	0.1324	0.2360	2.318	23.7
11.314	97.79	9.40	110	0.1365	0.2230	2.369	23.5
16.000	111.18	7.78	75.0	0.1443	0.2120	2.474	24.7

Av. (statistics only) 24.2 ± 0.3

ϕ^5 Scaling

ϕ = 73.15 W = 28.3 ± 0.6 Kt

Recommended preliminary hydrodynamic yield = 24.2 ± 2.5 Kt

* Weight of bomb, cab, and shield: 231,000 lb; equation of state same as air.

Table 2.3—FIREBALL YIELD [redacted] UPSHOT-KNOTHOLE 3)*

Analytic Solution

Data: EG&G Eastman films:
17201, 17202, 17203,
17204, 17205, 17206, 17207;
plus six Rapatronics

Ambient conditions:
Pressure (P_0), 0.863 bar
Density (ρ_0), 1.064 g/liter
Sound velocity (C_0), 0.337 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.500	9.09	32.91	1370	0.3721	79.29	1.759	0.173
0.707	11.20	25.97	845	0.3052	108.67	1.532	0.169
1.000	13.37	20.31	525	0.2620	136.71	1.465	0.174
1.414	15.89	16.16	330	0.2349	162.20	1.495	0.189
2.000	18.72	12.77	205	0.2115	183.78	1.459	0.189
2.828	21.82	9.72	117	0.1804	197.79	1.529	0.181
4.000	25.25	7.83	75	0.1748	205.11	1.637	0.195

Av. (statistics only) 0.181 ± 0.004

ϕ^5 Scaling

ϕ = 28.6 W = 0.26 ± 0.1 Kt

Recommended preliminary hydrodynamic yield = 0.18 ± 0.05 Kt

* Reiterated solution. Weight of bomb and cab, 33,400 lb; equation of state same as air. Owing to uncertainty in the equation of state and the mass, take yield uncertainty as 25 per cent.

Table 2.4—FIREBALL YIELD [redacted] UPSHOT-KNOTHOLE 4)

Analytic Solution

Data: EG&G Eastman films:
17301, 17302, 17303,
17305, 17306, 17307, 17308;
plus 10 Rapatronics

Ambient conditions:
Pressure (P_0), 0.686 bar
Density (ρ_0), 0.8764 g/liter
Sound velocity (C_0), 0.3311 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.333	46.5	21.5	585	0.1289	127.4	2.44	11.0
2.916	50.4	18.9	455	0.1310	122.0	2.49	10.9
3.645	54.7	16.6	355	0.1340	117.3	2.56	11.0
4.556	59.3	14.45	258	0.1354	113.3	2.56	10.8
5.695	64.5	12.8	208	0.1399	109.9	2.59	10.9
7.119	70.1	11.3	158	0.1429	106.9	2.58	10.8
8.899	76.4	9.9	122	0.1459	104.6	2.56	10.7
11.124	83.1	8.7	93	0.1498	102.9	2.52	10.6
13.905	90.8	7.74	73	0.1544	102.0	2.50	10.8
17.381	99.2	6.59	52	0.1600	101.7	2.43	10.8

Av. (statistics only) 10.8 ± 0.1

ϕ^5 Scaling

$\phi = 62.91$ W = 11.2 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 10.8 ± 1 Kt

Table 2.5—FIREBALL YIELD [redacted] (UPSHOT-KNOTHOLE 5)*

Analytic Solution

Data: EG&G Eastman films:
17401, 17402, 17403,
17405, 17406, 17407;
plus seven Rapatronics

Ambient conditions:
Pressure (P_0), 0.866 bar
Density (ρ_0), 1.036 g/liter
Sound velocity (C_0), 0.3314 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.250	6.13	54.15	3700	0.5368	44.35	3.864	0.317
0.3585	8.00	45.30	2570	0.4524	81.31	2.438	0.309
0.500	10.05	37.62	1775	0.3849	131.07	1.780	0.310
0.707	12.21	29.05	1090	0.3105	175.00	1.695	0.318
1.000	14.54	22.03	620	0.2525	207.50	1.687	0.305
1.414	17.06	16.58	350	0.2075	231.49	1.732	0.303
2.000	19.91	12.90	210	0.1845	249.97	1.962	0.312
2.828	23.04	10.15	130	0.1700	259.01	2.024	0.309
4.000	26.54	8.14	80.5	0.1650	262.43	1.990	0.297

Av. (statistics only) 0.309 ± 0.002

ϕ^5 Scaling

$\phi = 30.1$ W = 0.35 ± 0.1 Kt

Recommended preliminary hydrodynamic yield = 0.30 ± 0.06 Kt

* Reiterated solution. Used mass of bomb and cab, 16,000 lb; equation of state same as air. Yield uncertainty taken as 25 per cent.

[redacted]

Table 2.6—FIREBALL YIEL[redacted](UPSHOT-KNOTHOLE 6)

· Analytic Solution

Data: EG&G Eastman films:
17501, 17502, 17503,
17504, 17505, 17506, 17507,
17508, 17513, 17514

Ambient conditions:
Pressure (P_0), 0.852 bar
Density (ρ_0), 1.057 g/liter
Sound velocity (C_0), 0.3361 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.414	45.1	36.6	1680	0.1484	932.9	1.95	28.5
2.000	51.4	27.9	970	0.1334	896.6	2.06	26.0
2.828	58.15	21.6	595	0.1248	831.1	2.22	24.3
4.000	65.65	17.25	380	0.1242	762.2	2.45	24.5
5.657	74.30	14.18	257	0.1320	707.6	2.72	26.8
8.000	84.40	11.8	175	0.1429	669.1	2.87	29.0
11.314	96.50	9.91	122	0.1530	653.7	2.92	30.9
16.000	110.65	8.23	83	0.1600	647.9	2.69	29.5
20.000	121.35	7.36	65.5	0.1660	657.9	2.56	29.6
					Av. (statistics only)		27.7 ± 0.7
Data: Nine EG&G Rapatronics*							
1.819	49.45	29.3	1080	0.131	0.285	2.33	29.2
2.274	53.45	25.35	810	0.132	0.271	2.42	29.1
2.842	58.15	22.2	630	0.133	0.262	2.53	29.6
3.553	63.15	19.4	475	0.135	0.253	2.46	28.2
4.443	68.60	16.93	360	0.136	0.245	2.58	28.9
5.550	74.50	14.76	275	0.137	0.235	2.59	28.0
6.940	80.70	12.82	208	0.138	0.228	2.57	27.2
8.675	87.75	11.21	157	0.139	0.220	2.63	27.0
10.840	95.45	9.81	120	0.140	0.214	2.49	25.1
13.560	103.60	8.52	89	0.141	0.207	2.39	23.4
16.950	112.50	7.45	67	0.142	0.200	2.34	22.3
					Av. (statistics only)		27.1 ± 0.8

ϕ^5 Scaling

$\phi = 73.21$ $\quad$ $W = 28.8 \pm 0.3$ Kt

Recommended preliminary hydrodynamic yield = 27.4 ± 2.7 Kt

* Rapatronics does not include correction for small mass effect.

Table 2.7—FIREBALL YIELD[redacted]UPSHOT-KNOTHOLE 7)*

Analytic Solution

Data: EG&G Eastman films:
17601, 17602, 17603,
17604, 17605, 17606,
17607, 17608

Ambient conditions:
Pressure (P_0), 0.860 bar
Density (ρ_0), 1.037 g/liter
Sound velocity (C_0), 0.3482 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.000	57.7	30.9	1200	0.1390	51.14	2.284	52.6
2.828	65.8	24.31	745	0.1324	49.28	2.395	50.7
4.000	84.3	19.41	475	0.1324	45.15	2.535	49.1
5.657	84.5	16.00	325	0.1390	43.00	2.729	52.8
8.000	96.2	13.15	220	0.1450	41.27	2.733	53.2
11.314	110.2	10.81	145	0.1500	40.20	2.634	51.5
16.000	125.6	8.88	98	0.1550	39.70	2.589	51.6
22.62	143.9	7.29	64.5	0.1600	38.60	2.486	49.8

Av. (statistics only) 51.5 ± 0.5

ϕ^5 Scaling

$\phi = 82.72$ W = 52.1 ± 1 Kt

Recommended preliminary hydrodynamic yield = 51.5 ± 5 Kt

* Fireball asymmetric, different R-t curve from separate stations. Films 17605 to 17608, analyzed separately, give 51.8 Kt. Films 17601 to 17604 give 51.2 Kt.

Table 2.8—FIREBALL YIELD, EFFECTS (UPSHOT-KNOTHOLE 8)

Analytic Solution

Data: EG&G Eastman films:
17701, 17703, 17704, 17705,
17706, 17707, 17708, 17713,
17714

Ambient conditions:
Pressure (P_0), 0.825 bar
Density (ρ_0), 1.020 g/liter
Sound velocity (C_0), 0.336 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.414	45.04	33.4	1420	0.1241	2964	2.345	27.5
2.000	50.88	26.9	905	0.1260	2731	2.417	26.3
2.828	57.59	21.7	601	0.1285	2533	2.489	25.8
4.000	65.25	17.6	402	0.1318	2365	2.568	25.5
5.657	74.13	14.4	264	0.1357	2233	2.617	25.3
8.000	84.25	11.8	176	0.1418	2123	2.630	25.2
11.314	96.31	9.75	118	0.1478	2056	2.598	25.2
16.000	110.0	8.09	80	0.1564	2013	2.598	25.9
22.628	126.47	6.67	54	0.1633	2022	2.488	26.2

Av. (statistics only) 25.9 ± 0.3

ϕ^5 Scaling

$\phi = 72.50$ W = 26.4 ± 1 Kt

Recommended preliminary hydrodynamic yield = 25.9 ± 2.6 Kt

Table 2.9—FIREBALL YIELD [redacted] (UPSHOT-KNOTHOLE 9)

Analytic Solution

Data: EG&G Eastman films:
17801, 17802, 17803,
17804, 17805, 17806,
17807, 17808

Ambient conditions:
Pressure (P_0), 0.864 bar
Density (ρ_0), 1.0305 g/liter
Sound velocity (C_0), 0.3426 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.500	30.24	68.9	6900	0.1523	0.3230	2.089	33.1
0.707	34.56	56.2	3920	0.1553	0.3188	2.220	35.4
1.000	39.70	45.8	3230	0.1563	0.3160	2.290	36.4
1.414	45.29	36.84	1700	0.1553	0.3128	2.406	37.6
2.000	51.89	29.0	1070	0.1465	0.2879	2.401	32.6
2.828	59.29	22.32	760	0.1332	0.2931	2.333	29.3
4.000	67.78	17.98	4055	0.1323	0.2753	2.454	28.8
5.657	76.32	14.63	268	0.1332	0.2580	2.642	30.3
8.000	86.92	12.13	185	0.1463	0.2480	2.668	21.2
11.314	99.56	10.05	137	0.1534	0.2429	2.670	32.0
16.000	113.91	8.24	83	0.1572	0.2400	2.578	31.3

Av. (statistics only) 32.5 ± 2.7

Data: 11 EG&G Rapatronics

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.2500	23.67	111.5	15550	0.16249	0.3800	1.685	33.5
0.3535	27.17	88.1	9700	0.15390	0.3790	1.738	32.6
0.5000	31.06	68.8	5900	0.14394	0.3700	1.855	31.8
0.7070	35.28	54.2	3650	0.13846	0.3530	2.016	31.7
1.000	40.20	43.7	2360	0.13583	0.3360	2.203	33.1
1.414	45.70	35.0	1540	0.1375	0.3200	2.264	32.1
2.000	51.90	28.0	1000	0.1370	0.3020	2.356	31.4
2.828	59.25	22.65	650	0.1370	0.2920	2.449	31.5
4.000	67.30	18.20	415	0.13749	0.2750	2.619	31.9
5.657	76.70	15.02	285	0.14357	0.2640	2.740	33.5
8.000	87.50	12.26	188	0.14761	0.2560	2.675	32.6
11.314	100.20	10.10	126	0.15272	0.2500	2.646	32.5
16.000	114.60	8.37	85	0.16000	0.2480	2.597	33.2

Av. (statistics only) 32.4 ± 0.2

ϕ^5 Scaling

$\phi = 75.18$ W = 32.1 ± 0.4 Kt

Recommended preliminary hydrodynamic yield = 32.4 ± 3 Kt

[redacted]

Table 2.10—FIREBALL YIELD, GUN (UPSHOT-KNOTHOLE 10)

Analytic Solution

Data: EG&G Eastman films:
17903, 17904, 17907,
17908

Ambient conditions:
Pressure (P_0), 0.884 bar
Density (ρ_0), 1.075 g/liter
Sound velocity (C_0), 0.3393 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	33.30	37.40	1760	0.1452	0.1310	2.437	15.6
1.414	38.01	30.49	1220	0.1481	0.1270	2.524	16.0
2.000	43.46	24.82	770	0.1502	0.1243	2.601	16.3
2.828	49.65	19.72	490	0.1452	0.1206	2.560	15.1
4.000	56.66	15.85	322	0.1442	0.1168	2.636	14.9
5.657	64.71	12.97	212	0.1482	0.1132	2.676	15.0
8.000	73.91	10.55	138	0.1502	0.1105	2.638	14.7
11.314	84.87	8.83	97	0.1591	0.1092	2.667	15.6
16.000	97.38	7.29	64	0.1652	0.1097	2.567	15.6
					Av. (statistics only)		15.4 ± 0.2
Data: Nine EG&G Rapatronics							
1.000	33.05	41.4	2150	0.1810	0.1262	2.690	20.6
1.414	38.34	33.63	1450	0.1769	0.1326	2.458	19.4
2.000	44.17	26.13	860	0.1616	0.1345	2.330	17.0
2.828	50.69	20.51	540	0.1507	0.1335	2.347	15.9
4.000	57.85	16.05	328	0.1416	0.1291	2.217	13.6
5.657	65.87	12.58	200	0.1342	0.1230	2.170	12.0
8.000	75.48	10.07	126	0.1347	0.1149	2.443	12.7
11.314	84.90	8.49	89	0.1477	0.1097	2.638	14.4
16.000	97.18	7.17	62	0.1600	0.1088	2.751	16.1
					Av. (statistics only)		15.7 ± 1

ϕ^5 Scaling

$\phi = 64.10$ W = 15.0 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 15.5 ± 1.5 Kt

Table 2.11 — FIREBALL YIELD [redacted] UPSHOT-KNOTHOLE 11)*

Analytic Solution

Data: EG&G Eastman films:
171003, 171004, 171007,
171008, 171009, 171010,
171011, 171012

Ambient conditions:
Pressure (P_0), 0.824 bar
Density (ρ_0), 1.004 g/liter
Sound velocity (C_0), 0.3402 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.000	60.59	32.5	1350	0.1329	0.6533	2.242	61.1
2.828	68.75	26.1	855	0.1332	0.6150	2.294	59.0
4.000	78.05	21.1	565	0.1352	0.5790	2.493	61.2
5.657	88.75	17.08	370	0.1372	0.5490	2.573	60.9
8.000	100.78	13.78	240	0.1385	0.5228	2.583	58.7
11.314	115.15	11.3	160	0.1432	0.5022	2.589	58.4
16.000	131.18	9.28	107	0.1481	0.4870	2.553	57.8
22.628	150.23	7.71	72	0.1561	0.4784	2.504	58.7
32.000	169.66	6.36	48.6	0.1661	0.4795	2.476	62.1
					Av. (statistics only)		59.8 ± 0.5
Data: Four EG&G Rapatronics							
0.500	35.97	73.2	7600	0.1200	0.7698	1.999	57.9
0.707	40.40	59.1	4380	0.1280	0.6958	2.113	59.0
1.000	45.90	49.1	3020	0.1324	0.6520	2.256	61.1
1.414	52.09	39.5	1970	0.1326	0.6140	2.265	57.9
2.000	59.08	31.5	1260	0.1317	0.5758	2.332	55.5
2.828	66.99	25.4	810	0.1332	0.5398	2.462	55.5
4.000	76.59	20.73	545	0.1359	0.5100	2.710	58.9
5.657	86.55	16.8	405	0.1395	0.4842	2.664	56.5
8.000	98.54	13.71	238	0.1436	0.4652	2.662	55.8
11.314	112.66	11.31	160	0.1494	0.4502	2.671	56.4
16.000	127.28	9.27	106	0.1569	0.4440	2.653	58.0
22.628	148.19	7.81	75	0.1647	0.4442	2.582	59.3
32.000	170.70	6.45	51	0.1694	0.4530	2.484	59.8
					Av. (statistics only)		57.8 ± 1.5

ϕ^5 Scaling

ϕ = 86.22 W = 62 ± 1 Kt

Recommended preliminary hydrodynamic yield = 60 ± 6 Kt

* Eastman used as more reliable owing to paucity of Rapatronics points.

Table 2.12 — TIME-OF-ARRIVAL METHOD FOR YIELD

Shot No.	Model	Range to shot, ft	Calculated C_0	Measured C_0	Acoustic time	Shock time, MicB	Shock time (stop watch)	Δt	Time-of-arrival yield	Fireball yield*	Remarks
1	[redacted]	42,410	1103	1074	38.45		36.0	2.45	17.5	17.8	Stop watch and calculated C_0
2	[redacted]	60,246	1107	1120	54.4		51.4/51.6	2.9	26.0	24.2	Average stop watch and calculated C_0
3	[redacted]	54,567	1109	1115	49.2	48.32	48.7	0.5	0.3	0.18	Stop watch and calculated C_0
4	[redacted]	55,886	1108	1126	50.44	48.25	48.8/48.6	1.74	10.0	10.8	Average stop watch; C_0 calculated for 7000 ft
5	[redacted]	60,822	1100	1063	55.3	54.5	54.5	0.8	0.32	0.30	Stop watch and calculated C_0
6	[redacted]	76,473	1126	1123	68.1		65.1/64.9	3.1	29.0	27.4	Yield reported on measured value of C_0
7	[redacted]	45,380	1128	1146	40.2		36.8	3.4	55.0	51.5	Stop watch and calculated C_0
8	Effects	62,025	1112.5	1094	55.75	52.87		2.86	27.3	25.9	Height-of-burst correction of 0.68 sec
9	[redacted]	39,382	1123	1116	35.1	32.8	32.2	2.9	35.0	32.4	Stop watch and calculated C_0
10	Gun	61,600	1104	1110	55.5	53.1	53.0	2.5	16.4	15.5	Stop watch and measured C_0
11	[redacted]	55,640	1127.5		49.35		45.8	3.55	58.0	60.0	Stop watch and calculated C_0

* The uncertainty of the preliminary fireball yield is taken as 10 per cent; the uncertainty of the time-of-arrival yield is approximately $(0.2/\Delta t)^3$, which is usually about 20 per cent.

CHAPTER 3

OPERATION IVY

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3.1 GENERAL

This chapter deals with the preliminary fireball analysis of the bombs of the Operation Ivy series.

A short history and the purpose of the analytic-solution method for hydrodynamic yield are given in Chap. 2. The techniques are given in somewhat greater detail in Report J-16455, Mar. 4, 1953, Procedure for Analytic Solution on Fireball Growth. A formal paper, including the complete derivation for the solution, is planned for distribution in the late fall of this year as part of a volume entitled "Hydrodynamics of Strong Shocks."

This chapter is part of a preliminary series; the results are firmer than on other operations but may be considered preliminary in the following restricted sense:

1. The data are from final measurements as reported in EG&G Reports 1087 and 1086, Feb. 26, 1953.

2. Improved time corrections have not been applied to the films. On most bombs of small yield the uncertainty in the method of zero-time correction leads to some scatter in the data and requires further correction by improved techniques recently developed in Group J-10. On Mike and King shots, however, the long time scale of the fireball growth minimizes the uncertainty of the zero-time corrections; so it is doubtful that the yields will be markedly revised on this account.

3. No films have been reread. This presents no problem on King, which is probably the best fireball data in existence, [redacted] On Mike there is some question regarding possible asymmetry from the inhomogeneity of the atmosphere in the large region encompassed by the fireball, but it does not appear at present that the resulting asymmetry is large enough to materially alter the yield on Mike upon further study.

4. The solutions have not been reiterated. On Ivy the quality of the data is sufficiently good that reiteration may improve the constancy of the yield at various times but will hardly affect the final result. On either bomb the maximum departure of any single determination of the yield from the mean is less than 4 per cent.

The results on Mike and King are comparable to some of the best on other operations. However, there is a great deal of auxiliary information which can be used to correlate and evaluate the yields on these two weapons, which are referred to briefly in this paper. Following the present project in Group J-10 of reviewing all past bombs in a preliminary way,

techniques will be standardized and final reports will be rendered on each of the operations, together with more complete results from auxiliary methods.

3.2 MIKE

It is of interest to compare some of the previously quoted hydrodynamic yields from Mike because these indicate a smaller uncertainty in the yield than may generally be recognized. The first yield on Mike was reported as 11.7 Mt in Report JF-1192 on Nov. 1, 1952, the day of the shot. However, the ambient-air density used in this determination was 1.17 g/liter, obtained from readings aboard the USS Estes some 35 nautical miles from the bomb, and was considered satisfactory as a preliminary number. The final value of ambient-air density is 1.10 g/liter, and with this value the original data from the first film taken aboard the USS Estes gives a yield of 11.0 Mt for Mike. On Nov. 5, 1952, a yield of 12.3 Mt was reported in Report JF-1241, based solely on Rapatronics data; with the appropriate correction for revised air density, these data would now indicate a yield of 11.8. However, as recalled, errors were later found in these Rapatronics data, and these would, in any case, now be considered unreliable. The fireball yield on Mike was again reported as 10.35 Mt in Report J-15470, Jan. 9, 1953, based on some readings of the final EG&G curve received by TWX. On Mar. 9, 1953, another yield of 10.9 Mt was reported in Report J-16500, based on a photostatic copy of the final EG&G radius-time curve but before the improved calculation of the factor F was developed during Operation Upshot-Knothole. The results in this chapter come from a redetermination of the original data, using the same averaging procedure on the ϕ vs t curve, and a calculation of the factor which was used through Operation Upshot-Knothole and the other preliminary reports in the present series. The present number of 10.4 Mt differs by only 6 per cent from the number deduced from data obtained the day of the shot; all other reliable yields are intermediate between these two.

Interesting and corroborative data are obtained from the mass-motion studies by D. F. Seacord, Jr., Ivy Project 6.2 Report, WT-627, June 1953, Blast-Wave Mass-motion Measurements. In the mass-motion experiment the slope of the shock front and the slope of the mass-motion lines are measured directly. They are important parameters in the analytic solution and can be applied directly in the analytic solution without recourse to the calculation for peak pressures, as is done on ordinary bombs. Moreover, material velocity and density compression at the shock front are measured directly without recourse to the theoretical equation of state in Report LADC-1133. As reported in Report J-17776, May 17, 1953, Fireball Yields on IBM Problem M, the analytic solution was found valid down to a pressure level of 3 atm. This justifies the use of the analytic solution on the mass-motion data considerably beyond the region of fireball growth. The data encompassed by the mass-motion experiment go from a time of 0.7 sec, a radius of 1900 meters, and a pressure level of 12 atm down to a time of 5.6 sec, a radius of 5244 meters, and a pressure of 3 atm. The analytic-solution yield from mass motion of mortar puffs near the ground was 10.1 ± 0.4 Mt on Mike. This result is expected to be low because, by this time, the effects of atmospheric inhomogeneity on the blast wave will reduce the apparent yield at the surface and increase the apparent yield at altitude. A similar solution applied to mass motion of the high-altitude gun bursts encompassed measurements up to a 24,000-ft altitude on Mike and show, as expected, high apparent yields at this altitude.

Other information from long-range measurements is contained in two papers: Preliminary Blast Summary, Operation Ivy, Report J-15162, Nov. 22, 1952, and Report J-15273, Dec. 22, 1952. In the first of these papers, Table 1 shows that the apparent yield from peak-pressure measurements by Sandia Corporation ranged downward from a value of 10.3 Mt at Engebi, where the yield has most meaning, to very much lower values at long ranges, where the effect of atmospheric refraction has reduced the apparent yield at the ground. The same paper showed yields from the time-of-arrival method as scattered values between 10.3 and 12.5 Mt, based on the Sandia Corporation preliminary time-of-arrival measurements. In the second of these papers the time-of-arrival curve for Mike is compared with the theoretical curve of 10

Mt in Fig. 4, showing excellent agreement. At the same time Fig. 5 compares later peak-pressure data from Sandia Corporation, with essentially the same results as reported in November. Positive durations were compared in Fig. 6, but, as expected from long-range effects (particularly thermal reinforcement of the blast wave), the positive durations are much longer. In summary, it appears that the long-range measurements were consistent with a value such as 10 Mt for Mike rather than values such as 5 Mt.

There is a disagreement between the ambient value for density of 1.10 g/liter as used by Group J-10 in comparison with 1.15 g/liter as used by EG&G for the ϕ^5 scaling method. Group J-10 has used the lower figure because it is representative of the average density over the fireball surface, whereas the value of 1.15 g/liter refers only to the density at sea level.

3.3 FIREBALL PERTURBATIONS

There are a considerable number of possible perturbations to the fireball which are of interest because of the extremely large size on Mike and because of disagreement between the fireball yield, the predictions, and the early radiochemical yields. These are properly part of a more complete and formal study, but some pertinent points are briefly indicated below.

3.3.1 Ground Shock and Cratering

The question here is how much energy was lost by the fireball through the production of ground shock. First of all, a reflection factor of 2 was used on the fireball data, and a correction for ground shock would only increase the apparent yield of Mike. However, in Report LA-1529, Soil Pressures and Energy Transfers on Mike Shot, Oct. 10, 1952, it was shown that the energy transfer on Mike would probably be on the order of 0.1 per cent or, in any case, not exceeding 1 per cent. The physical reason for this small percentage is the fact that the rate of work per unit area of a shock front is proportional to the material velocity. At high pressures both the material and shock velocity are very much lower in soil than the corresponding velocities in air. From this it was concluded that production of ground shock abstracts a negligible amount of energy from the fireball.

3.3.2 Mass Effect of Fireball

This problem resolves itself into two parts: one concerns the 500 tons of shielding material around the Mike bomb; the other concerns the dust loading of the fireball. [redacted] Bethe has estimated that several hundred thousand tons of dust were eventually present in the cloud; others pointed out that the presence of this dust would increase the apparent yield of the bomb by changing the gamma of the air on the interior. However, according to the usage of the analytic solution, this objection is not valid. The analytic solution is an energy integration over the air in the fireball. If substantial additional mass were present by virtue of dust loading, a rigorous derivation would integrate over the mass of dust in addition or would be included as part of the mass-effect correction. If such a calculation were performed by integrating over the mass of dust separately, it would increase rather than reduce the total energy, despite the fact that the average gamma of the dust-air mixture might be changed in such a way as to indicate a higher value of gamma and, consequently, a lower value of apparent yield. It is doubtful from hydrodynamic arguments that the dust which was eventually present in the cloud was present during the fireball stage. In fact, in the fireball pictures for Mike the region of strong dust loading showed itself as a belt of different light intensity near the ground, which did not seriously affect the fireball radii as measured at substantial heights above the ground. Finally, the measured slopes of the Mike fireball are characteristic of a clean bomb of small mass effect.

3.3.3 Scaling

Occasionally the question has been raised regarding the validity of scaling up to a weapon the size of Mike. The point here is that the analytic solution was a preparation for Mike precisely because it was a method for determining the yield without recourse to scaling. There are reasons for this failure of similarity scaling, which are part of the arguments leading to the analytic solution: radiative transport, the mass effect of the bomb, and variations in gamma of the air at strong shocks. There is no question, however, of the fundamental validity of the cube-root scaling law, at low pressures, in its proper context. It is an interesting point that concurrently with this work on Ivy, Jack Whitener of this group was performing experiments with the sonic anemometer in which he generated a shock wave from a spark whose yield is approximately 10^{-12} Kt. The same theoretical blast curves which were used to compare the long-range blast characteristics on Mike were also used successfully by Whitener to study the shock characteristics of his spark gap; a change in energy of 10^{19} is involved here.

3.3.4 Atmospheric Inhomogeneity

This question will arise in two ways: by changing the equation of state at the shock front and by changes in gamma on the interior. With regard to the variations at the shock front, the derivation of the analytic solution shows that ρ_0 appears in the final expression solely as a result of the Rankine-Hugoniot conditions at the shock front. As such, an average value over the surface is properly applicable. Variations in gamma on the interior appear as an average value over the volume, but these are fairly insensitive to changes in ρ_0. The ambient density has been used as 1.10 g/liter; this variation of 5 per cent from the surface value represents an estimate of the average value over the fireball surface, and the estimate is probably accurate to 1 per cent.

3.3.5 Radiating Shock Front

Does the energy radiated from the shock front materially change the apparent energy at the shock as determined through the Rankine-Hugoniot relations? Here again the effect, if any, would be to raise the apparent yield rather than lower it. Furthermore, even if this effect were sufficiently strong that, above a certain pressure, the Rankine-Hugoniot shock curve became isothermal, it would make a barely detectable difference in the relation between pressure and velocity. Similar questions involve the contribution to the total energy by radiation density. Order-of-magnitude calculations show that these corrections are negligible, certainly below 3000 atm, whereas the present number is usually based on measurements below 700 atm. However, the analytic solution has been applied at various times up to peak pressures of 10,000 to 30,000 atm and with reasonable consistency between the apparent yield at these pressure levels compared with the yield determined at low-pressure levels. This is taken as reasonable empirical assurance that the failures in the equation of state are small even at these extremely high pressure levels.

3.3.6 Slow Rise of Shock

This problem concerns the validity of the Rankine-Hugoniot equation if the shock is not, in fact, a sharp rise. Now the Rankine-Hugoniot equations represent the conservation of mass, momentum, and energy between gases in two separate states, one ambient, the other shocked. It is not strictly necessary that there be a sharp discontinuity for determining the peak pressure or other hydrodynamic variables from the measurement of the shock velocity but merely that there be no source or sink of energy, mass, or momentum across the boundary zone and that the subsequent decay in pressure be small compared with the rise time. Furthermore, if the pressure rise behind the shock wave were sufficiently thick so that the process were adiabatic, supersonic velocities would not be observed at its leading edge. Finally, adiabatic rise would mean there could be no late fireball.

3.3.7 Gamma Rays

The question was raised whether gamma rays from the bomb absorbed in front of the shock wave would preheat the air, increasing the ambient-sound velocity and hence the apparent shock velocity. Order-of-magnitude calculations show that this effect is small. There is perhaps a more important aspect of the gamma-ray question, i.e., because of the large shock radii on Mike, most gamma rays were captured within the fireball and could manifest themselves as a bona fide source of hydrodynamic energy within the blast, which is then rapidly communicated to the shock front; whereas on a smaller bomb these gamma rays would escape the shock wave. However, this is at best only a few per cent of the total energy of the bomb.

3.3.8 Thermal Preheating

The question here is whether thermal radiation from the bomb itself, preceding the shock wave, might be absorbed and might preheat the air in a fashion similar to that described for gamma rays. Order-of-magnitude calculations again show that this increase in ambient temperature is probably small. This point was considered in Report LA-1214, Rate of Growth of Atomic Fireballs, and there it was shown that the Rankine-Hugoniot equations are still probably valid over a region including such a precursor. The increase in the shock velocity (because of preheating) would be compensated by the decrease in pressure (because of the radiating shock) in such a way that the final shock velocity would be essentially the same as it would be in the absence of radiative transport.

3.3.9 Thermal Effect on Ground

The question here is whether the thermal effect on the ground preceding the shock would lead to increased radii through precursor formation just as it is observed on air bursts. The point here is that most of Mike fireball was over water on which no thermal effect takes place. Another question is whether the thermal radiation on the interior of the bomb may not heat the ground surface within the fireball and be converted to hydrodynamic energy at this time. The point here is that, if energy from the interior of the fireball is radiated to the ground surface, it must at the same time represent a compensating rarefaction within the interior of the fireball, as demanded by conservation of energy.

3.3.10 Neutron Reinforcement

The question here is whether the relatively large numbers of neutrons on Mike might be captured and degraded thermally on the interior of the shock, whereas on smaller bombs such neutrons escape the fireball. This question is valid, and the phenomena represent a bona fide energy source to Mike, which has been estimated by W. E. Ogle as a fraction of a megaton. This energy will be readily apparent at the shock front because the neutrons are captured in the region of high density immediately behind the shock.

3.3.11 Thermal Reinforcement

The point of interest here is whether thermal radiation which might escape beyond the shock front on a smaller bomb would be captured on Mike because of the longer path lengths involved. This would be a bona fide source of hydrodynamic energy to the fireball but involves only the energy radiated prior to breakaway, which has always been known to be small. Using the illumination curves by Lewis Fussell, we have recently calculated this fraction again for many yields and find that there is actually an increase in this fraction; roughly calculated it is a factor of 2 between bombs on the order of 1 Kt and bombs on the order of 1 Mt. The energy involved here, however, is on the order of 5 parts in a million compared with the total yield for radiation between 5000 and 7000 A; it is probably only an order of magnitude larger when all wave lengths are considered, which is still negligible.

To summarize these possible perturbations, it appears that nearly all the effects either would have negligible effect or, if anything, would raise the yield rather than decrease it. At

present it appears that only neutron reinforcement within the shock wave represents any substantial increase in apparent energy at the shock front. For diagnostic purposes this fraction might be subtracted from the hydrodynamic yield for comparisons with ordinary bombs. For purposes of hydrodynamic effects this reinforcement represents a bona fide increase in hydrodynamic energy, and the fireball numbers correctly represent the total hydrodynamic yield.

3.4 KING SHOT

The King fireball is probably the most ideal of that of any bomb.

It is of interest to compare the earlier reported values of yield. The first report on King is contained in the Cursory Report by Ogle soon after shot day, at which time the apparent yield was 580 Kt, based on an ambient density of 1.15 g/liter, again from an early estimate. Subsequent revisions of the density downward, as in the case of Mike, reduce this apparent yield on King to 554 ± 10 Kt. Another determination was reported as 544 Kt in Report J-15470, Jan. 9, 1953, Fireball Yield on Ivy, based on a few points received by TWX from final EG&G data. The data for this analysis were so meager that yields could be computed at only three times, and for this reason the results were considered unreliable. In Report J-16500, Mar. 9, 1953, the yield was reported as 536 Kt, based on a photostatic copy of final results from EG&G, but this was before the inclusion of higher order terms as developed for the mass-effect correction during Operation Upshot-Knothole. The inclusion of higher order terms, using the same photostatic data, was reported in Report J-17754, May 15, 1953, at which time the revised yield became 549 Kt. The data in this chapter are based on the redetermination of the average radius-time curve, using the same techniques as developed during Operation Upshot-Knothole, and result in the value of 555 Kt. Curiously enough the original number, when corrected downward for density, is 0.2 per cent below the present number. At the same time all numbers, except the 536 Kt, have been within 1 per cent of the present recommended value of 550 Kt.

There is considerable corroborative evidence from low-pressure measurements on King shot which supports this value of the yield, but the argument is of less interest on King, where there is no question on yields, than in establishing the validity of the theoretical curves on Mike, where the uncertainty on the total yield was considerably greater. In Report J-15273, Dec. 22, 1952, Preliminary Blast Summary, Operation Ivy, preliminary results of Sandia Corporation are compared with the theory. Figure 1 of the report shows the time-of-arrival curve, which is for the most part "pencil width" correct. In fact, there was originally some uncertainty regarding the drop error on King. By use of the theoretical time-of-arrival curve, with the calculation for the finite height of burst, the burst location was determined from the preliminary time-of-arrival data of Sandia Corporation. Strikingly good agreement was obtained for the actual burst location with the location as determined by Lewis Fussell from triangulation cameras. The mere fact that the time-of-arrival curve was sufficient to determine the error in burst location is good evidence for remarkable precision of the time-of-arrival curve and the yield on King. In the same paper Fig. 2 shows a comparison of the peak-pressure measurements over the ideal surfaces and over thermal surfaces taken from the work in Report LA-1406. Although the peak-pressure measurements are not very reliable for establishment of a yield, they do confirm the validity of the theoretical curves and show, as on Mike, the long-range rarefaction effect setting in beyond 15,000 to 20,000 ft. Again, as on Mike, the positive durations were considerably longer than would be expected in a homogeneous medium because of long-range effects, probably thermal reinforcement deep within the shock wave.

There are insufficient points from Seacord's low-mass-motion mortar data on Project 6.2 to establish an analytic yield as was done on Mike. However, the peak pressures and the material velocity are in good agreement with the theoretical curve for 550 Kt.

A preliminary comparison of the raw time of arrival vs distance data from rocket data by NOL on Project 6.13 shows excellent agreement between King and the theoretical curves,

but this comparison is fairly insensitive to yield. As in the case of the mortar data on Mike, by use of the fitted curve from their report, an attempt was made to apply the analytic solution to the NOL rocket-trail data, but the success was only moderate. At high pressures the yield is apparently 558 Kt, decreasing to a value of 517 Kt at 15 atm. However, it was noted that these data were not in agreement with the fireball curves in the region where they were supposedly pegged to the fireball data to establish the zero times. Through correspondence with them the reason was established as being apparently the use of preliminary fireball data by NOL. On a number of other bombs the rocket-trail data have been applied to the analytic solution and usually exhibit either a constant downward trend in yield or a constant upward trend in yield, starting with approximately correct values near the region of the fireball growth. For these reasons the rocket data are not considered sufficiently accurate for use with the analytic solution pending further study.

Table 3.1 — FIREBALL YIELD, MIKE*

Analytic Solution

Data: EG&G Eastman films:
16102, 16103, 16104,
16110, 16111; plus
three Rapatronics

Ambient conditions:
Pressure (P_0), 0.951 bar
Density (ρ_0), 1.10 g/liter
Sound velocity (C_0), 0.348 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	φ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Mt
22.628	492.0	23.3	690	0.1387	180.1	2.447	10.5
32.000	560.0	18.8	450	0.1399	173.5	2.557	10.8
45.256	637.5	15.16	290	0.1402	164.8	2.643	10.5
64.000	727.6	12.40	193	0.1439	158.8	2.651	10.4
90.512	829.9	10.13	126	0.1479	154.0	2.594	10.2
128.000	949.0	8.36	85	0.1539	150.8	2.556	10.2
181.024	1087.6	6.90	57.5	0.1599	148.5	2.452	10.0
						Av. (statistics only)	10.4 ± 0.1

ϕ^5 Scaling

$\phi = 272.8$ $W = 11.2 \pm 0.6$ Mt

Recommended preliminary hydrodynamic yield = 10.4 ± 0.5 Mt

*Ambient conditions were taken at average fireball height; a reflection factor of 2 was applied to the yield. The EG&G value of yield was based on $\rho_0 = 1.15$ g/liter; it would become 10.7 Mt for $\rho_0 = 1.10$ g/liter.

Table 3.2—FIREBALL YIELD, KING*

Analytic Solution

Data: EG&G Eastman films:
16201, 16202, 16203,
16204

Ambient conditions:
Pressure (P_0), 0.946 bar
Density (ρ_0), 1.10 g/liter
Sound velocity (C_0), 0.347 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n_2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.828	109.0	38.53	1900	0.1239	6.150	2.194	574.6
4.000	123.2	31.51	1270	0.1260	5.670	2.290	563.7
5.657	139.5	25.44	810	0.1281	5.260	2.428	562.4
8.000	157.8	20.54	535	0.1306	4.900	2.526	555.6
11.314	179.3	16.80	360	0.1355	4.602	2.676	573.7
16.000	203.6	13.76	240	0.1409	4.387	2.651	563.3
22.628	232.2	11.24	157	0.1448	4.225	2.607	548.3
32.000	265.2	9.22	106	0.1489	4.100	2.566	538.5
45.256	303.4	7.61	71	0.1548	4.023	2.489	532.8
64.000	348.5	6.31	47.5	0.1619	4.008	2.400	535.4

Av. (statistics only) 555 ± 5 Kt

ϕ^5 Scaling

$\phi = 132.0$ W = 595 ± 5 Kt

Recommended preliminary hydrodynamic yield = 550 ± 10 Kt

*Rapatronics data were not used owing to gross disagreement with Eastman data. The yield was based on $\rho_0 = 1.149$ g/liter; it should be revised down to 569 Kt for $\rho_0 = 1.10$ g/liter.

CHAPTER 4

OPERATION TUMBLER-SNAPPER

By F. B. Porzel

Sept. 1, 1953

4.1 GENERAL

This chapter summarizes the preliminary fireball analysis of the hydrodynamic yields for the Tumbler-Snapper series.

The history and purposes of the analytic-solution method for hydrodynamic yields are given in Chap. 2. The techniques are given in somewhat greater detail in Report J-16455, Mar. 4, 1953, Procedure for Analytic Solution on Fireball Growth. A formal paper, including the complete derivation and background for the analytic solution, is planned for distribution in the late fall of this year as part of a volume entitled "Hydrodynamics of Strong Shocks."

The results in this chapter are preliminary in the following sense:

1. The data are from preliminary measurements by EG&G in the files of Pogo Staff (J-Division, LASL). The final film data sheets of EG&G (EG&G Report 1093) were received after the work of this chapter was completed. In general, the preliminary data were from fewer films and were read by fewer people than the final data. Apart from any improvement in the readings, this means that the statistical uncertainty of the average radius-time curve is greater than it will be for the final data.

2. No revision has been made of the zero-time correction as calculated by EG&G. A considerable part of the scatter in the present data is believed to be due to the procedure of establishing the zero times for the Eastman films by pegging to the Rapatronics data. Recent studies by Group J-10 have shown promising techniques for establishing this zero-time correction more precisely, but a great deal of computation work is required to revise each of the original data points determined by EG&G.

3. No films have been reread. In many cases the apparent discrepancies in the data indicate the requirement for rereading some of the films; this is particularly true on Snapper 5.

4. In general, no solutions have been reiterated. Because of the scatter in the data, the first and second derivatives of the radius-time curve cannot be resolved directly from the raw data with the accuracy that would be desired; this results in fluctuations of the apparent yield at various times, without seriously affecting the average yield. The reiteration of the solution is tantamount to fitting a smooth curve within the statistical uncertainty of the data. The effort in the reiteration is probably not warranted here because the final data will be revised for the reasons mentioned in items 1, 2, and 3.

Following the preliminary review of all operations, data will be revised according to a standard procedure, and final yields will be obtained. The purpose of these preliminary analyses is, in part, to study the effect of uncertainties in the original data on the final yield.

The results in this chapter have important implications because of the nature of Operation Tumbler. The purpose of that operation was to investigate the theory of surface effects on blast from atomic bombs, and the results from this operation have been widely used by military establishments almost to the exclusion of data from all other tests. As it turns out, the yields on three out of the four bombs are seriously in question. For example, the data on free-air-pressure measurements by NOL, using the rocket-trail technique, have been represented as the "Tumbler established norm" for atomic bombs and are widely used. Although there are questions regarding the calculating technique used by NOL, this free-air curve is closely related to the fireball analysis and should be in agreement, regardless of radiochemical results. It seems curious at present, in view of the fact that three of the four bombs can be seriously in error (ranging from a revision upward of 40 per cent on Tumbler 1 to a revision downward of 10 per cent on Tumbler 3), that discrepancies were not noted in the NOL analysis. The question of yield can be resolved in part by applying the analytic solution to the rocket-trail raw data because it presently appears that the free-air curves from the first two bombs of the Tumbler series cannot scale at the high pressures encompassed by the rocket-trail data and the failure in scaling would, in fact, be in the direction of giving lower apparent scaled yields.

4.2 COMMENTS ON SPECIFIC BOMBS

4.2.1 Tumbler 1 and 2

These were both relatively high airdrops [redacted] There is a marked discrepancy between the values of 1.45 Kt from the analytic solution as compared with the radiochemical number of 1.06 on Tumbler 1 and 1.16 on Tumbler 2. There has been considerable question for some time in Group J-10 concerning the yields of these two weapons.

The most definite confirmation of the discrepancy occurred late last winter in preparation of the height-of-burst curves in Report LA-1406. In general, peak-pressure data are too poor for information about the yield because of large and erratic reductions in peak pressure due, in turn, to surface effects and also because of a lack of a rigorous theory in the region of Mach reflection, even over ideal surfaces. The situation is different for Tumbler 1 and 2. By last winter a theoretical free-air curve had been derived and was amply confirmed on Operation Ivy. Both Tumbler 1 and 2 were high airdrops; so many of the measurements were in the region of regular reflection (where reflection theory is rigorous) or in the region shortly thereafter when the Mach stem is small (where the uncertainty is small). Also, the thermal effect is small because of the high height of burst and, in any case, would reduce pressures. Now, a comparison of the peak-pressure data from Tumbler 1 and 2 with these theoretical curves showed that the peak pressures measured near these bombs were abnormally high using the radiochemical yields at the time. A preliminary analysis was then made of Tumbler 1 using the analytic solution; this gave values ranging from 2 Kt at early times down to less than 1 Kt at late times. However, the mass-effect correction was only being developed at the time, and it was correctly believed that this mass effect accounted for the apparently high numbers. The low numbers near 1 Kt were found to have occurred because part of the original data by EG&G had been read beyond breakaway, which was verified by an examination of the slopes and use of early rocket data. This left little question that the yield on Tumbler 1 was probably around 1.5 Kt, which was in much better agreement with the peak-pressure data from ground measurements.

[redacted] The strong mass effect is readily apparent in the data because of abnormally high values of slopes on the ln R – ln t plot. In fact, ϕ^5 scaling could not be applied to these bombs because it requires that the slope be exactly 0.4, and the slopes on these bombs never reach this low a value. During Operation Upshot-Knothole, however, the mass-effect correction was developed and included in the analytic solution and was applied with reasonable success to [redacted]

Tumbler 1 and 2. This considerably alleviates the uncertainty concerning the validity of the analytic-solution yield on Tumbler 1 and 2.

There is even earlier evidence regarding these yields, which are contained in Annex XV, Free-air Pressures from Fireball Measurements, May 15, 1952, Project 19.2, Operation Tumbler; this LASL paper was published as a preliminary report on Tumbler by AFSWP. In this paper the fireball yields were measured on a relative scale using a procedure suggested in Report LA-1214 (later called constant Mach-number scaling). The point in this procedure is an unambiguous determination of whether or not scaling is valid between any two bombs. The results of that analysis showed clearly that such scaling was not valid, and, in fact, this failure of scaling was a primary reason for the development and use of the analytic solution on Operation Ivy.

In Annex XV no attempt was made to scale Tumbler 1 and 2 to other bombs because no smaller bombs were available for comparison, and, even in comparison with a 3.5-Kt bomb (Buster-Baker), "abnormally high" values were obtained for the yields. Instead, no attempt was made to scale these weapons with others, and the best that could be done was to make a relative comparison between Tumbler 1 and 2, which indicated that Tumbler 1 was probably about 10 per cent lower than Tumbler 2. This unfortunately turned out to be the ratio later obtained by radiochemistry. It now appears that the low value of Tumbler 1 was due to the strong influence of measured radii at late times, which had been read beyond breakaway on Tumbler 1 by EG&G. It also appears that the abnormally high values obtained from simple scaling were real, even though only crudely approximate.

It has been pointed out by H. Plank, and it seems to be confirmed on even earlier operations, that high airdrops often result in fractionation, which is not always detected by an inconsistency in the radiochemical samples. It is suggested that this is a possible reason if the radiochemical values on Tumbler 1 and 2 are actually low.

4.2.2 Tumbler 3

Tumbler 3 wa[redacted] The analytic-solution yield of 28.5 is significantly different from the radiochemical value of 30.7 Kt and the ϕ^5 scaling value of 31.5 Kt.

At the time it was fired, Tumbler 3 was at an altitude of 3450 ft, the highest air burst that had been fired up to that time. A similar bomb, fired at 2200 ft, the Effects shot on Operation Upshot-Knothole, showed evidence of fractionation, evidently because of the high height of burst; and this raises the question of whether similar fractionation occurred on Tumbler 3.

There is another indication that the value of 28.6 Kt obtained on Tumbler 3 is approximately correct.[redacted]

In Annex XV (mentioned in Sec. 4.2.1), the yield for Tumbler 3 was also investigated. In the case of Tumbler 3 there was no real concern over the mass effect, and moreover bombs of both lower and higher yields were available for scaling comparisons. In Annex XV the scaled yield for Tumbler 3 ranged from approximately 26 Kt (which was least reliable because it was a comparison with a much smaller bomb) up to 28.5 Kt (which was probably most reliable because it was a comparison[redacted] The yield for Tumbler 3 was estimated at the time as 27.5 ± 2 Kt.

4.2.3 Tumbler 4 (Snapper 1)

Tumbler 4 was[redacted]fired at a relatively low altitude. This is a bomb [redacted]The agreement is considered

excellent between the analytic-solution value of 19.7 Kt, the radiochemical value of 19.2 Kt, and the ϕ^5 scaling value of 20.0 ± 1 Kt.

4.2.4 Snapper 2

Snapper 2 was [redacted] fired on a tower, where the mass effect is more serious than on Tumbler 4 or Tumbler 3 and more nearly comparable to the average experience in Nevada. The agreement between the analytic-solution number of 13.0 Kt is considered fair in comparison with the radiochemical value of 12.0 Kt and a ϕ^5 scaling value of 13.0 Kt.

4.2.5 Snapper 3 and 4

[redacted] were tower shots. They are part of a logical sequence later including [redacted] A comparison of these results is contained [redacted] p. 2 under the discussion of the results [redacted] The agreement is fair [redacted] between the analytic-solution value of 11.9 Kt, the radiochemical value of 11.1 Kt, and a ϕ^5 scaling value of 12.0 Kt. There is excellent agreement between the analytic-solution value of 16.9 Kt and the ϕ^5 scaling value of 17.0 Kt [redacted] but a definite discrepancy exists between these numbers and the radiochemical value of 14.6 Kt. At present we have no explanation regarding the discrepancy.

4.2.6 Snapper 5

Snapper 5 was [redacted] fired from a tower, and no attempt is made to quote the hydrodynamic yield for it. The fireball pictures from this bomb are without doubt the poorest that have ever been observed on any bomb. Very large asymmetrical effects are present, presumably due to the mass of shielding and equipment around the cab, and cursory examination of the fireball films shows that it will be difficult ever to obtain reliable data from this weapon.

It is not clear why the fireball on this weapon should be as badly unsymmetrical as it is. Reasonably good results were obtained o[redacted]uring Operation Upshot-Knothole, both involving greater shielding masses [redacted] arge protuberances were observed in the fireball, which are explained either by late mass effects or by chemical combustion of the concrete shield on the tower. [redacted] these protuberances appear after breakaway and probably did not seriously affect the yields. It seems possible that the change in time scale [redacted] may have caused the protuberances to appear before breakway, when it seriously affects the fireball data.

It is planned to reread the films [redacted] before making further analyses, particularly in view of the fact that the radius-time curves are so vastly different from different camera stations. It is not known how much of the data have been read beyond breakaway, and this could be difficult to answer [redacted]

Data from Eastman films fall into two ϕ vs time bands; films 13800, 13801, 13802, and 13803 define a band resulting in a yield higher than that given by films 13805, 13806, 13807, and 13810. An average of all eight Eastmans plus three Rapatronic points gives a yield of 18.4 ± 0.8 Kt (statistics only). Due to the tremendous scatter of data, even within the defined bands, the uncertainty is increased to ±3. The ϕ^5 scaling method of EG&G gives 17.6 ± 1.2 Kt. The best that can presently be done is to state that the hydrodynamic yield lies between 12 and 20 Kt, with a most probable value around 18 Kt.

[redacted]

Table 4.1—FIREBALL YIELD, TUMBLER 1*

Analytic Solution

Data: EG&G Rapatronics

Ambient conditions:
Pressure (P_0), 0.885 bar
Density (ρ_0), 1.07 g/liter
Sound velocity (C_0), 0.340 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.177	8.10	95.8	11500	0.5053	357	1.852	1.12
0.250	10.22	74.2	6850	0.4058	573	1.711	1.33
0.354	12.60	59.3	4370	0.3198	812	1.893	1.64
0.500	15.16	45.2	2550	0.2568	1020	1.972	1.73
0.707	17.81	34.2	1430	0.2128	1155	1.985	1.63
1.000	20.80	26.2	860	0.1838	1245	1.987	1.52
1.414	24.06	20.3	525	0.1648	1289	2.101	1.49
2.000	27.64	15.8	320	0.1508	1289	2.278	1.48
2.828	31.52	12.3	190	0.1409	1245	1.887	1.11

Av. (statistics only) 1.45 ± 0.07

Recommended preliminary hydrodynamic yield = 1.45 ± 0.20 Kt

*The yield comparing diameters with Ranger A at 1.27 Kt was 1.28 ± 0.13 Kt. There were no timing markers on Eastman films; therefore Rapatronic films were the sole data source. ϕ^5 scaling not possible owing to variation in ϕ.

Table 4.2—FIREBALL YIELD, TUMBLER 2*

Analytic Solution

Data: Seven Rapatronics plus
Eastman films 13101, 13105

Ambient conditions:
Pressure (P_0), 0.852 bar
Density (ρ_0), 1.05 g/liter
Sound velocity (C_0), 0.337 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.177	8.28	97.81	11800	0.4951	397	1.723	1.11
0.250	10.42	78.31	7600	0.4000	630	1.587	1.31
0.354	12.83	60.76	4600	0.3180	890	1.884	1.75
0.500	15.43	46.07	2650	0.2530	1115	1.915	1.77
0.707	18.14	35.07	1550	0.2120	1265	1.713	1.51
1.000	21.18	27.09	910	0.1857	1365	2.186	1.82
1.414	24.48	21.02	562	0.1674	1408	2.127	1.64
2.000	28.13	16.28	332	0.1520	1408	2.201	1.55
2.828	32.13	12.48	195	0.1370	1368	2.016	1.24

Av. (statistics only) 1.46 ± 0,09

Recommended preliminary hydrodynamic yield = 1.45 ± 0.20 Kt

*The yield comparing diameters with Tumbler 1 was 1.29 ± 0.13 Kt. There was a wide variation in data from Rapatronic film and Eastman film; Rapatronics plus Eastman films 13101 and 13105 are most consistent.

Table 4.3—FIREBALL YIELD, TUMBLER 3*

Analytic Solution

Data: EG&G Eastman films: 13201, 13203, 13205, 13206; plus four Rapatronics

Ambient conditions:
Pressure (P_0), 0.770 bar
Density (ρ_0), 0.954 g/liter
Sound velocity (C_0), 0.337 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.000	53.07	26.03	860	0.1093	3368	2.416	26.5
2.828	59.60	21.29	580	0.1154	3006	2.571	26.6
4.000	67.19	17.58	395	0.1243	2733	2.724	27.6
5.657	76.14	14.65	275	0.1342	2550	2.839	29.0
8.000	86.59	12.25	190	0.1446	2435	2.847	29.9
11.314	99.19	10.21	130	0.1543	2380	2.771	30.3
16.000	113.55	8.41	87	0.1592	2364	2.596	29.1

Av. (statistics only) 28.4 ± 0.6

ϕ^5 Scaling

$\phi = 76.2$ W = 30.8 ± 1.5 Kt

Recommended preliminary hydrodynamic yield = 28.5 ± 1.0 Kt

*Reiterated solution.

Table 4.4—FIREBALL YIELD, TUMBLER 4 (SNAPPER 1)*

Analytic Solution

Data: EG&G Eastman films: 13301, 13303, 13305, 13306; plus six Rapatronics

Ambient conditions:
Pressure (P_0), 0.844 bar
Density (ρ_0), 1.021 g/liter
Sound velocity (C_0), 0.340 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.000	47.32	25.07	790	0.130	192	2.511	20.0
2.828	53.78	20.34	520	0.1325	180	2.515	19.1
4.000	61.08	16.48	340	0.135	170	2.615	19.2
5.657	69.49	13.45	225	0.139	162	2.626	18.9
8.000	79.01	11.05	150	0.145	154	2.683	19.1
11.314	90.25	9.20	105	0.154	148.5	2.799	20.4
16.000	102.67	7.70	71	0.167	143	2.812	21.4

Av. (statistics only) 19.7 ± 0.4

ϕ^5 Scaling

$\phi = 68.0$ W = 20.0 ± 1.0 Kt

Recommended preliminary hydrodynamic yield = 19.7 ± 1.0 Kt

*Reiterated solution.

Table 4.5—FIREBALL YIELD, SNAPPER 2*

Analytic Solution

Data: EG&G Eastman films:
13400, 13401, 13403,
13404, 13406, 13407,
13410; plus five Rapatronics

Ambient conditions:
Pressure (P_0), 0.858 bar
Density (ρ_0), 1.027 g/liter
Sound velocity (C_0), 0.342 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.378	46.58	20.75	550	0.1315	124	2.570	13.5
2.828	49.51	18.62	440	0.1322	119	2.650	13.4
3.364	52.80	16.74	358	0.1330	116	2.719	13.5
4.000	56.24	15.09	290	0.1345	112.5	2.717	13.2
4.757	59.89	13.53	232	0.1350	109	2.696	12.7
5.657	63.84	12.17	185	0.1360	106	2.724	12.6
6.727	68.15	11.00	150	0.1380	104	2.724	12.5
8.000	72.50	9.89	122	0.1395	101	2.734	12.4
9.514	77.53	8.98	100	0.1420	99	2.754	12.4

Av. (statistics only) 12.9 ± 0.2

ϕ^5 Scaling

$\phi = 62.0$ W = 13.0 ± 2.0 Kt

Recommended preliminary hydrodynamic yield = 13.0 ± 0.5 Kt

*Reiterated solution.

Table 4.6—FIREBALL YIELD, SNAPPER 3*

Analytic Solution

Data: EG&G Eastman films:
13600, 13601, 13602,
13603, 13605, 13606,
13607, 13610; plus
four Rapatronics

Ambient conditions:
Pressure (P_0), 0.858 bar
Density (ρ_0), 1.044 g/liter
Sound velocity (C_0), 0.340 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.00	43.00	23.4	690	0.134	117.7	2.30	11.8
2.50	46.60	20.0	505	0.132	113.2	2.34	11.4
3.13	50.59	17.3	380	0.132	108.8	2.50	11.7
3.91	54.82	15.3	295	0.135	104.7	2.60	12.0
4.89	59.80	13.4	225	0.139	101.3	2.68	12.3
6.11	64.98	11.8	176	0.142	98.5	2.70	12.3
7.64	70.60	10.3	133	0.145	96.3	2.60	11.8
9.55	77.00	9.2	105	0.150	94.6	2.60	12.0
11.94	83.85	8.2	81	0.154	93.6	2.54	11.9
14.93	91.55	7.2	63	0.158	93.2	2.46	11.8

Av. (statistics only) 11.9 ± 0.1

ϕ^5 Scaling

$\phi = 61.9$ W = 12.0 ± 2 Kt

Recommended preliminary hydrodynamic yield = 12.0 ± 0.5 Kt

*Reiterated solution.

Table 4.7—FIREBALL YIELD, SNAPPER 4*

Analytic Solution

Data: EG&G Eastman films:
13700, 13701, 13702,
13703, 13705, 13706,
13707, 13710; plus
four Rapatronics

Ambient conditions:
Pressure (P_0), 0.862 bar
Density (ρ_0), 1.042 g/liter
Sound velocity (C_0), 0.340 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.00	45.1	24.55	770	0.137	148.2	2.556	16.9
2.50	48.35	21.11	570	0.138	143.2	2.652	17.1
3.13	53.2	19.31	472	0.140	138.7	2.632	16.7
3.91	57.75	16.29	337	0.141	134.7	2.640	16.3
4.89	62.8	14.31	260	0.144	131.0	2.706	16.6
6.11	68.5	12.66	204	0.148	128.7	2.726	16.9
7.64	74.5	11.18	156	0.152	126.2	2.722	17.0
9.55	81.4	9.90	122	0.156	125.1	2.688	17.1
11.94	89.0	8.77	94	0.160	124.9	2.644	17.2
14.93	97.4	7.70	72	0.164	125.1	2.596	17.3

Av. (statistics only) 16.9 ± 0.1

ϕ^5 Scaling

$\phi = 66.12$ W = 17.0 ± 0.7 Kt

Recommended preliminary hydrodynamic yield = 17.0 ± 0.5 Kt

*Reiterated solution.

CHAPTER 5

OPERATION GREENHOUSE

By F. B. Porzel

Oct. 1, 1953

5.1 GENERAL

This chapter is part of a series; it summarizes the preliminary fireball analyses for the hydrodynamic yields for the bombs of the Greenhouse series.

The history and purposes of the analytic-solution method for hydrodynamic yields are given in Chap. 2. Techniques are given in somewhat greater detail in Report J-16455, Mar. 4, 1953, Procedure for Analytic Solution on Fireball Growth. A formal paper, including the complete derivation and background of the analytic solution, is planned for distribution in the late fall of this year as part of a volume entitled "Hydrodynamics of Strong Shocks."

The results of this paper are preliminary in the following sense:

1. The data are from final measurements by EG&G as reported in an extract of their final report, EG&G Report 1161, Aug. 12, 1953.

2. No revision has been made of the zero-time correction as calculated by EG&G. A considerable part of the scatter in the present data is believed to be due to the procedure of establishing zero time for the Eastman films by pegging to the Rapatronics data. Recent studies by Group J-10 have shown promising techniques which establish this zero-time correction more precisely, but a great deal of computation work is required to revise each of the original data points determined by EG&G.

3. No films have been reread. This does not appear to be a serious question on Greenhouse, except possibly in the case of George shot, which had a large mass effect readily apparent at early times. The George fireball is clean and symmetrical at late times when the analysis is made.

4. In general, no solutions have been reiterated. Because of scatter in the primary data, the first and second derivatives of the radius-time curve cannot be resolved with the accuracy that would be desired; this results in fluctuations in the apparent yield at various times without seriously affecting the average yield. Reiteration of the solution is tantamount to fitting the smooth curve within the statistical uncertainty in the data. The effort in the reiteration is probably not warranted here because the final data will be revised for the reasons mentioned in items 1, 2, and 3.

Following the preliminary review of all operations, data will be revised according to a standard procedure, and final yields will be obtained. The purpose of these preliminary analyses is, in part, to study the effect of uncertainties in the original data on the final yield.

5.2 COMMENTS ON GREENHOUSE

The analytic-solution results on Greenhouse fall into two categories: excellent agreement in the case of Dog, Easy, and Item in comparison with both radiochemistry and ϕ^5 scaling and significant departures from both in the case of George. The tabulated values of yield are:

Shot	Analytic solution	Radiochemistry	ϕ^5 scaling
Dog	82.3 ± 1.4	82.9	82 ± 0.9
Easy	47.0 ± 0.5	46.7	47.2 ± 0.6
Item	45.7 ± 0.5	45.7	47.1 ± 0.7
George	249 ± 3	214.5	257.6 ± 3.2

In the case of Dog, Easy, and Item, the radiochemical values are all within the statistical uncertainty of the analytic solution, without allowing for standard errors in the measurement (as it is estimated in the recommended preliminary hydrodynamic yields). In these three cases the agreement between the analytic solution and radiochemistry is better than 1 per cent. In the case of ϕ^5 scaling the agreement is equally good on Dog and Easy, but ϕ^5 scaling is about 3 per cent higher on Item than both radiochemistry and the analytic solution. The agreement between radiochemistry and ϕ^5 scaling on these bombs is not significant because the empirical constant used by EG&G in ϕ^5 scaling is pegged to radiochemical results of Operations Ranger, Buster, and Greenhouse (which included Dog, Easy, and Item but did not include George).

The agreement between radiochemistry and the analytic solution on these three bombs is remarkable. Both the analytic solution and radiochemistry are absolute yields in their own right but are based on completely different concepts. The absolute values in the analytic solution depend not only on the validity of the wave forms but ultimately on the equation of state of air as derived by Porzel in Report LADC-1133, based in turn on theoretical computations by Bethe, Hirschfelder, Curtiss, and Kirkwood. The absolute values in radiochemistry depend on the energy per fission in nuclear reactions, with estimates made by Fred Reines a number of years ago on the fraction of energy released prior to an arbitrary time (such as 10 msec). The agreement here is considerable reassurance that, at least on fission weapons, both methods are on a consistent and probably sound foundation.

The discrepancy between the fireball yield and radiochemistry on George has been known for some time. Because ϕ^5 scaling is pegged to radiochemical results and because it is independent of the hydrodynamics in the analytic solution, the relatively good agreement between ϕ^5 scaling and the analytic solution significantly bears on the discrepancy between the analytic solution and radiochemistry. The yield reported in this chapter definitely confirms the disagreement between radiochemistry and fireball on the first of the thermonuclear weapons. By now it is almost a rule that, except for cases of fractionation, the two methods agree on all fission weapons and furthermore that on every thermonuclear weapon the analytic solution is always significantly higher than radiochemistry.

In view of the agreement obtained on most fission weapons, there is no question that this discrepancy between the analytic solution and radiochemistry will be resolved one day, and the yields for thermonuclear weapons will become consistent. Meanwhile, the implications with regard to use of the yields seem to be as follows: The processes of energy transformation are extremely complex in both situations. Both yields are on a common basis in that they partially neglect the contribution to total energy from delayed or secondary nuclear radiation. The analytic solution neglects the gamma rays and neutrons which escape the fireball prior to breakaway time but includes the contribution to hydrodynamic energy of the thermal degradation of the radiation captured within the shock prior to breakaway. The analytic solution neglects the thermal radiation from the bomb prior to breakaway, but this is a negligibly small fraction of

the total yield. A principal advantage of the analytic solution is that it measures total hydrodynamic yield, within the limitations cited above, without reference to the source of the energy. Radiochemistry does not pretend to measure total hydrodynamic yield but counts only the energy released from known nuclear reactions. For most diagnostic purposes of weapon design, the radiochemical yield is applicable, using the total hydrodynamic yield as a check against the existence of unknown processes. For the purposes of hydrodynamic effects, such as blast and probably thermal radiation, the analytic-solution results are applicable, regardless of a discrepancy with radiochemistry.

Table 5.1—FIREBALL YIELD, DOG*

Analytic Solution

Data: EG&G Eastman films: E267, E268, E270, E337, E339 and Fastax films: F260, F261

Ambient conditions:
Pressure (P_0), 1012.2 bar
Density (ρ_0), 1.1677 g/liter
Sound velocity (C_0), 0.3485 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	46.0	52.6	3420	0.1589	66.12	2.32	89.0
1.414	52.8	42.5	2250	0.1570	65.83	2.36	88.9
2.000	60.6	34.1	1490	0.1540	65.19	2.39	87.4
2.828	69.3	27.3	930	0.1500	64.07	2.39	83.4
4.000	79.2	21.5	580	0.1430	62.00	2.32	75.1
5.657	90.3	17.2	375	0.1401	59.71	2.52	77.0
8.000	102.8	14.0	248	0.1441	57.39	2.71	81.6
11.314	117.6	11.5	165	0.1490	55.71	2.69	81.3
16.000	134.3	9.45	112	0.1540	54.69	2.61	80.3
22.628	154.1	7.79	73	0.1589	54.26	2.54	80.0
32.000	177.2	6.47	50	0.1660	54.56	2.47	81.6

Av. (statistics only) 82.3 ± 1.4

ϕ^5 Scaling

$\phi = 88.69$ W = 82.0 ± 0.9 Kt

Recommended preliminary hydrodynamic yield = 82.3 ± 1.5 Kt

*Reiterated solution.

Table 5.2—FIREBALL YIELD, EASY

Analytic Solution

Data: EG&G Eastman films:
E495, E496, E497, E498,
E501, E502, E505 plus
four Rapatronics

Ambient conditions:
Pressure (P_0), 1.0102 bar
Density (ρ_0), 1.163 g/liter
Sound velocity (C_0), 0.3480 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	41.8	45.1	2550	0.1408	40.6	2.36	49.1
1.414	47.5	36.1	1650	0.1398	38.8	2.33	45.9
2.000	54.1	29.3	1100	0.1420	37.11	2.51	48.0
2.828	61.7	23.8	720	0.1437	35.80	2.56	47.9
4.000	70.4	19.2	460	0.1437	34.50	2.60	46.9
5.657	80.3	15.6	310	0.1472	33.30	2.72	48.4
8.000	91.8	12.5	197	0.1490	32.60	2.62	46.3
11.314	105.2	10.4	135	0.1512	32.00	2.60	45.8
16.000	120.2	8.53	89	0.1560	31.40	2.53	45.0

Av. (statistics only) 47.0 ± 0.5

ϕ^5 Scaling

ϕ = 79.47   W = 47.2 ± 0.6 Kt

Recommended preliminary hydrodynamic yield = 47.0 ± 1.0 Kt

Table 5.3—FIREBALL YIELD, GEORGE*

Analytic Solution

Data: EG&G Eastman films:
E697, E698, E699, E700,
E709, E710, E711, E712,
E713, E714 and Fastax
films: F701, F703, F704,
F705, F706, F707

Ambient conditions:
Pressure (P_0), 1.007 bar
Density (ρ_0), 1.545 g/liter
Sound velocity (C_0), 0.3497 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	55.9	70.5	6200	0.1942	17.47	1.97	240.7
1.414	65.1	56.3	3800	0.1830	18.67	2.03	250.3
2.000	75.2	44.0	2400	0.1671	19.24	2.02	234.4
2.828	86.4	34.5	1520	0.1562	19.25	2.17	235.2
4.000	98.9	27.4	940	0.1505	18.92	2.38	244.0
5.657	113.1	22.1	625	0.1489	18.46	2.52	249.5
8.000	129.2	17.8	405	0.1489	18.02	2.62	253.9
11.314	148.0	14.5	268	0.1503	17.58	2.74	261.0
16.000	169.0	11.9	178	0.1554	17.27	2.73	264.6
22.628	194.1	9.79	120	0.1594	17.23	2.60	257.3
32.000	223.0	7.97	77	0.1600	17.23	2.52	250.9

Av. (statistics only) 249 ± 3

ϕ^5 Scaling

ϕ = 111.7   W = 257.6 ± 3.2 Kt

Recommended preliminary hydrodynamic yield = 250 ± 5 Kt

*Original EG&G ϕ–t data corrected for zero time.

[redacted]

Table 5.4—FIREBALL YIELD, ITEM

Analytic Solution

Data: EG&G Eastman films:
E801, E802, E803,
E804, E805, E806

Ambient conditions:
Pressure (P_0), 1011.9 bar
Density (ρ_0), 1.163 g/liter
Sound velocity (C_0), 0.3485 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	39.9	47.2	2800	0.1699	32.3	2.30	45.8
1.414	46.0	37.9	1810	0.1651	32.8	2.35	46.2
2.000	52.9	30.3	1160	0.1600	33.0	2.40	46.1
2.828	60.7	24.1	730	0.1530	32.8	2.41	44.0
4.000	69.3	19.2	470	0.1486	32.0	2.55	44.0
5.657	79.3	15.6	310	0.1514	31.2	2.80	48.0
8.000	90.8	12.8	208	0.1558	30.8	2.74	47.8
11.314	104.3	10.5	137	0.1577	30.6	2.60	45.6
16.000	119.5	8.56	90	0.1593	30.5	2.47	43.6

Av. (statistics only) 45.7 ± 0.5

ϕ^5 Scaling

ϕ = 79.37 W = 47.1 ± 0.7 Kt

Recommended preliminary hydrodynamic yield = 45.7 ± 1.0 Kt

[redacted]

CHAPTER 6

OPERATION BUSTER-JANGLE

By F. B. Porzel and D. F. Seacord, Jr.

Nov. 20, 1953

6.1 GENERAL

This chapter is the fifth in a series summarizing the first fireball analyses with the analytic solution for the hydrodynamic yields of nuclear weapons of past operations. Herein are presented the analyses of the Buster series and Jangle-Surface.

The analytic-solution method for hydrodynamic yields and its application to past operations are discussed briefly in Chaps. 2 to 5 and references 1 and 2.

The results presented in this paper are preliminary in the following sense:

1. The basic data are from film measurements by EG&G as reported in Buster-Jangle Fireball Data, Report 1089, Aug. 13, 1953.
2. No films have been reread nor has any attempt been made to correct zero times as calculated by EG&G.
3. In general, solutions have been reiterated; this has been necessary because of a scarcity of data in those cases.

Following the completion of a preliminary analysis of all bombs for which fireball data are available, the procedure will be standardized and final hydrodynamic-yield numbers will be determined. Any major change will probably be due to the zero-time correction mentioned in item 2. A considerable part of the scatter in the present data is believed to be due to the procedure of establishing zero times for the Eastman films by pegging to the Rapatronics data. Continuing studies by Group J-10 indicate promising techniques which establish the Eastman zero times more precisely.

6.2 COMMENTS ON INDIVIDUAL SHOTS

6.2.1 Buster-Able

A single film, coupled with the minute yield, precluded the application of the analytic solution. Fireball photographic data for Buster-Able consist of a diameter-time tabulation over a range of 4 msec from one film. The data are insufficient to attempt an evaluation of the yield because of poor space resolution for such a small explosion and because breakaway should have occurred during the first frame or two of the cameras, which had been set for speeds and intensities expected of a nuclear explosion.

6.2.2 Buster-Baker

Twelve Eastman films were utilized in obtaining the average ϕ curve; there is no ambiguity because of grouping of films, but serious scatter exists in data, presumably owing to zero-time correction. For comparison with the analytic-solution yield of 3.94, radiochemistry is given as 3.49 and EG&G ϕ^5 scaling as 3.8. Scaling to Ranger A gave values[2] of 3.06 to 3.19, depending upon the time at which scaling is accomplished, but this was based on a yield for Ranger A which is now believed low.

Baker exhibits a characteristic seen on all small bombs where breakaway occurs at considerably higher pressures than on larger bombs. For this reason the range of pressures encompassed by reliable data is smaller than would be desired to satisfactorily define the slope and its derivative over a reasonable range, and the uncertainty in yield is high, accordingly.

6.2.3 Buster-Charlie

Eleven Eastman films provided the basic data; as in Baker serious scatter exists among these films. The hydrodynamic yield of 13.8 is in good agreement with both radiochemistry (14.0 ± 0.2) and ϕ^5 scaling (13.7 ± 0.2).

6.2.4 Buster-Dog

A single Eastman film, taken at the CP, merely provides a guide as to what the proper ϕ curve was. Fortunately the scatter from frame to frame was small, and reasonable ϕ values could be deduced. Reiteration was considered invalid in view of the fundamental uncertainty posed by a single film. The hydrodynamic yield of 20.3 is lower than both ϕ^5 scaling and radiochemistry (21.2 and 21.0, respectively); this is not excessive in view of the lack of data for the resolution required by the analytic solution.

6.2.5 Buster-Easy

Nine Eastman films, with excessive scatter, resulted in a hydrodynamic yield of 30.3 in good agreement with ϕ^5 scaling of 30.6 but below the radiochemistry value of 31.4. The difference is not considered excessive in view of the scatter in data between films, attributed to zero-time correction.

6.2.6 Jangle-Surface

Six Eastman and two Fastax films were available; the scatter in data from film to film is the worst encountered thus far. Fortunately Rapatronics data at early times were available, and the zero times of the Eastman and Fastax films were thereby corrected. After correction the data fell into three distinct categories: four Eastmans with a high rounded ϕ-t average, two Eastmans with a lower and flatter ϕ-t average, and two Fastax with an extremely low and flat ϕ-t average. Since Ranger A and Tumbler 1 and 2 all have similarly shaped ϕ-t curves and [redacted] it is expected that the Jangle-Surface ϕ-t curve should have the same general shape, modified for a reflection factor of 2. Because they had similar shapes, the four Eastmans grouped together were taken to be representative data; the lowness of the two Eastmans and two Fastax is at present unexplained.

On the basis of these four Eastman films, the hydrodynamic yield of Jangle-Surface is ~1.9 Kt compared to a radiochemistry value of 1.19. No ϕ^5-scaling value of yield was attempted because of differences in slope. This value of 1.9 Kt seems inordinately high in comparison with the radiochemistry value of 1.2 Kt but is in fair agreement with the analytic-solution yields [redacted] Although it would be hazardous to attribute better than 25 per cent accuracy to the analytic-solution yield on the Surface shot because of the grouping of cameras, it seems clear that Jangle-Surface [redacted] is significantly higher than the radiochemistry values.

Should this high yield again be confirmed after procedures have been standardized and a final hydrodynamic yield has been reported, it will have important implications because of the widespread use to which the Jangle-Surface data have been put in the analysis of effects.

REFERENCES

1. F. B. Porzel, Procedure for Analytic Solution on Fireball Growth, Report J-16455, Mar. 4, 1953.
2. H. E. Grier and staff, Technical Photography, Buster-Jangle Project 10.3 Report, WT-417, December 1952.

Table 6.1—FIREBALL YIELD, BUSTER-BAKER*

Analytic Solution

Data: EG&G Eastman films:
10502, 10503, 10504,
10505, 10506, 10507,
10511, 10512, 10513,
10514, 10515, 10516

Ambient conditions:
Pressure (P_0), 0.840 bar
Density (ρ_0), 1.032 g/liter
Sound velocity (C_0), 0.336 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	26.33	28.1	1000	0.128	40.5	2.31	3.86
1.414	29.83	22.8	660	0.131	37.8	2.46	3.92
2.000	33.85	18.5	430	0.135	35.6	2.57	3.98
2.828	38.50	15.2	290	0.140	33.8	2.65	4.05
4.000	43.88	12.4	193	0.144	32.5	2.57	3.88

Av. (statistics only) 3.94 ± 0.04

ϕ^5 Scaling

ϕ scaling with Ranger A	W = 3.1 Kt
ϕ = 49.2	W = 3.8 Kt

Recommended preliminary hydrodynamic yield = 3.9 ± 0.4 Kt

*Reiterated solution.

Table 6.2—FIREBALL YIELD, BUSTER-CHARLIE*

Analytic Solution

Data: EG&G Eastman films:
10701, 10702, 10704,
10705, 10706, 10711,
10712, 10715, 10713,
10714, 10716

Ambient conditions:
Pressure (P_0), 0.835 bar
Density (ρ_0), 1.022 g/liter
Sound velocity (C_0), 0.338 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	33.15	36.9	1700	0.142	12.8	2.46	14.2
1.414	37.78	30.0	1150	0.145	12.3	2.54	14.4
2.000	43.12	24.4	750	0.147	11.9	2.65	14.8
2.828	49.26	20.4	525	0.149	11.6	2.60	14.3
4.000	56.30	16.0	325	0.149	11.3	2.57	13.8
5.657	64.34	12.9	210	0.147	11.0	2.53	13.0
8.000	73.47	10.4	135	0.150	10.7	2.60	13.3
11.314	84.25	8.7	94	0.154	10.5	2.57	13.3
16.000	96.46	7.1	62	0.160	10.5	2.49	13.3

Av. (statistics only) 13.8 ± 0.2

ϕ^5 Scaling

$\phi = 63.59$ W = 13.7 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 13.8 ± 0.5 Kt

*Reiterated solution.

Table 6.3—FIREBALL YIELD, BUSTER-DOG*

Analytic Solution

Data: EG&G Eastman film:
10810

Ambient conditions:
Pressure (P_0), 0.832 bar
Density (ρ_0), 1.012 g/liter
Sound velocity (C_0), 0.340 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	36.44	38.7	1880	0.130	20.6	2.26	19.1
1.414	41.29	31.1	1225	0.131	19.2	2.27	18.1
2.000	46.84	25.1	790	0.132	18.0	2.47	18.7
2.828	53.14	20.4	525	0.136	17.0	2.66	19.5
4.000	60.50	16.9	360	0.143	16.2	2.85	21.0
5.657	69.14	14.0	245	0.151	15.8	2.95	22.1
8.000	79.16	11.6	170	0.160	15.6	2.98	23.5

Av. (statistics only) 20.3 ± 0.7

ϕ^5 Scaling

$\phi = 69.45$ W = 21.2 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 20.3 ± 1.0 Kt

*Solution based on one film (at CP).

Table 6.4—FIREBALL YIELD, BUSTER-EASY

Analytic Solution

Data: EG&G Eastman films:
10904, 10905, 10906,
10912, 10914, 10915,
10916, 10919

Ambient conditions:
Pressure (P_0), 0.838 bar
Density (ρ_0), 1.035 g/liter
Sound velocity (C_0), 0.337 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	38.7	45.2	2550	0.154	27.7	2.26	31.2
1.414	44.3	36.0	1650	0.150	27.2	2.32	30.7
2.000	50.6	28.8	1050	0.147	26.5	2.42	30.4
2.828	57.7	23.0	670	0.144	25.7	2.51	30.0
4.000	65.8	18.5	440	0.143	24.7	2.55	29.2
5.657	75.1	15.0	285	0.145	23.8	2.64	29.5
8.000	85.7	12.2	188	0.148	23.1	2.75	30.3
11.314	98.2	10.2	127	0.156	22.6	2.73	31.2

Av. (statistics only) 30.3 ± 0.3

ϕ^5 Scaling

$\phi = 74.40$ W = 30.6 ± 0.3 Kt

Recommended preliminary hydrodynamic yield = 30.3 ± 1.0 Kt

Table 6.5—FIREBALL YIELD, JANGLE-SURFACE*

Analytic Solution

Data: EG&G Eastman films:
11002, 11004, 11005, 11007

Ambient conditions:
Pressure (P_0), 0.872 bar
Density (ρ_0), 1.106 g/liter
Sound velocity (C_0), 0.332 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.189	26.1	27.9	980	0.179	27.3	2.45	2.07
1.414	28.1	24.7	770	0.172	27.8	2.43	2.00
1.681	30.1	22.0	610	0.166	28.0	2.39	1.92
2.000	32.3	19.5	480	0.161	28.1	2.36	1.84
2.378	34.6	17.4	380	0.157	28.1	2.37	1.80

Av. (statistics only) 1.93 ± 0.05

ϕ^5 Scaling

None

Recommended preliminary hydrodynamic yield = 1.9 ± 0.5 Kt

*Reiterated solution, based on four Eastmans, in preference.

CHAPTER 7

OPERATION RANGER

By F. B. Porzel and D. F. Seacord, Jr.

Nov. 23, 1953

7.1 GENERAL

This chapter is one of a series summarizing the first fireball analyses with the analytic solution for the hydrodynamic yields of nuclear weapons of past operations; herein are presented the analyses of the Ranger series.

The analytic-solution method for hydrodynamic yields and its application to past operations are discussed in Chaps. 2 to 6 and reference 1.

The results presented in this chapter are preliminary in the following sense:

1. The basic data are from film measurements by EG&G as reported in Ranger Fireball Data, Report 1087, Aug. 10, 1953.
2. No films have been reread.
3. No corrections have been applied to the zero times, as calculated by EG&G.
4. The reiteration procedure was applied to three shots: B_2, E, and F.

In all probability the hydrodynamic yields herein reported cannot be improved nor will the gross uncertainty be reduced. There are no early-time Rapatronics to use in correcting the zero times of the Eastman films. It should be realized that fireball photography was in its infancy at the time of Ranger, and hence the scatter in data is much more serious (and seemingly incapable of correction) than in succeeding operations where techniques have been greatly improved.

7.2 COMMENTS ON INDIVIDUAL SHOTS

7.2.1 Ranger A

[redacted]

Four Eastman films were available for deriving the basic ϕ-t curve. The scatter in data indicates the necessity for a zero-time correction, but no early Rapatronics data exist for accomplishing this. All films had been read well into breakaway, but examination of the ϕ curve establishes, with a fair degree of accuracy, where breakaway occurred and thus indicates the point beyond which the data are unreliable. The gross oscillations in the ϕ-t curve can be smoothed by using the curves from Tumbler 1 and 2 as a guide to the general shape.

The uncertainty in average ϕ at a given time is of the order of 1 or 5 per cent in energy; allowing a similar factor for the lack of shape resolution, as it might differ from Tumbler 1 and 2, an uncertainty of 10 per cent in yield is indicated. Furthermore, in view of the state of fireball photography at this time, systematic errors may increase this uncertainty to as much as 20 per cent.

The hydrodynamic yield of 2.0 Kt is compared with a radiochemistry value of 1.25. A value of 1.4 was obtained by comparison with Sandstone X-ray,[2] but a consideration of the relative mass effect between these bombs would indicate that similarity scaling is hardly reliable. [redacted]

7.2.2 Ranger B_1

Five Eastman films, with moderate scatter, were analyzed, and a smooth yield vs time curve resulted, with an average of 6.9 Kt. For comparison final radiochemistry gives 7.83 and Sandstone X-ray scaling, 7.2. The analytic-solution value appears quite reliable because of the small statistical uncertainty without reiteration.

7.2.3 Ranger B_2

Four Eastman films were available; one film was definitely in error and was not included in the analysis. After reiteration, an extremely flat yield curve was obtained, having an average value of 7.43 Kt. Radiochemistry has reported 7.95 and Sandstone X-ray scaling gives 6.7.

7.2.4 Ranger E

Three Eastman films were available for ϕ-t curves; a complete lack of agreement among the three prevented the application of the analytic solution. On such a small weapon breakaway occurs at about 2 msec, and the scatter in data prior to 1 msec is extremely serious. Because of too few reliable films, the fact that no zero-time correction is possible, and the small time spread covered, the uncertainty in the data during the times of interest leads to a wide variation in possible yields. Pending further study, no hydrodynamic yield is quoted at this time, but there is no assurance that a reliable yield can ever be obtained with these data.

REFERENCES

1. F. B. Porzel, Procedure for Analytic Solution on Fireball Growth, Report J-16455, Mar. 4, 1953.
2. R. A. Houghten, Analysis of Fireball Growth at Ranger, Ranger Report, Vol. 3, WT-203, February 1951.

Table 7.1—FIREBALL YIELD, RANGER A

Analytic Solution

Data: EG&G Eastman films:
EG&G 114, 115, 179, 180

Ambient conditions:
Pressure (P_0), 0.880 bar
Density (ρ_0), 1.094 g/liter
Sound velocity (C_0), 0.335 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.7070	18.3	35.4	1580	0.210	13.2	2.25	2.12
0.8406	19.8	31.2	1240	0.197	13.8	2.25	2.08
1.000	21.4	27.3	930	0.183	14.2	2.25	1.99
1.189	23.0	24.1	730	0.174	14.5	2.32	2.00
1.414	24.7	21.3	575	0.167	14.6	2.20	1.83
1.681	26.5	18.8	450	0.160	14.7	2.39	1.92
2.000	28.3	16.9	360	0.160	14.6	2.63	2.11

Av. (statistics only) 2.01 ± 0.04

Scaling to Sandstone X-ray

W = 1.4 ± 0.2 Kt

Recommended preliminary hydrodynamic yield = 2.0 ± 0.5 Kt

Table 7.2—FIREBALL YIELD, RANGER B_1*

Analytic Solution

Data: EG&G Eastman films:
EG&G 123, 124, 125,
207, 108

Ambient conditions:
Pressure (P_0), 0.877 bar
Density (ρ_0), 1.082 g/liter
Sound velocity (C_0), 0.337 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
2.000	38.7	21.3	575	0.138	6.96	2.10	6.83
2.828	44.0	16.9	360	0.134	6.56	2.31	6.88
4.000	49.9	13.6	235	0.135	6.20	2.41	6.83
5.657	56.7	11.0	150	0.137	5.87	2.49	6.76
8.000	64.5	9.1	102	0.145	5.59	2.58	7.08
11.314	74.0	7.6	69	0.152	5.50	2.44	6.86

Av. (statistics only) 6.87 ± 0.04

Scaling to Sandstone X-ray

W = 7.4 ± 0.7 Kt

Recommended preliminary hydrodynamic yield = 6.9 ± 0.3 Kt

*No reiteration.

~~SECRET RESTRICTED DATA~~

Table 7.3—FIREBALL YIELD, RANGER B_2*

Analytic Solution

Data: EG&G Eastman films:
EG&G 216, 225, 226

Ambient conditions:
Pressure (P_0), 0.895 bar
Density (ρ_0), 1.149 g/liter
Sound velocity (C_0), 0.330 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	φ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.708	27.3	38.8	1880	0.110	9.68	1.98	7.54
1.000	30.6	31.2	1240	0.113	8.63	2.12	7.41
1.414	34.4	25.2	810	0.117	7.76	2.30	7.49
2.000	38.8	20.5	535	0.122	7.06	2.39	7.38
2.828	43.9	16.7	350	0.126	6.50	2.52	7.38
4.000	49.7	13.7	235	0.132	6.05	2.59	7.40

Av. (statistics only) 7.43 ± 0.03

Scaling to Sandstone X-ray

W = 6.7 ± 0.7 Kt

Recommended preliminary hydrodynamic yield = 7.4 ± 0.2 Kt

*Reiterated solution.

Table 7.4—FIREBALL YIELD, RANGER F*

Analytic Solution

Data: EG&G Eastman films:
EG&G 233, 234, 235,
243, 244

Ambient conditions:
Pressure (P_0), 0.886 bar
Density (ρ_0), 1.097 g/liter
Sound velocity (C_0), 0.336 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	φ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	36.8	40.3	2050	0.135	21.7	2.23	22.5
1.414	41.9	32.5	1350	0.136	20.6	2.35	22.5
2.000	47.6	26.2	860	0.137	19.5	2.45	22.4
2.828	54.1	21.1	565	0.137	18.5	2.45	21.3
4.000	61.5	17.0	365	0.138	17.6	2.50	20.9
5.657	70.0	13.8	240	0.139	16.8	2.58	20.7
8.000	79.7	11.3	158	0.144	16.1	2.67	21.3
11.314	91.2	9.4	108	0.152	15.7	2.70	22.1

Av. (statistics only) 21.7 ± 0.3

Scaling to Sandstone X-ray

W = 22.0 ± 2.0 Kt

Recommended preliminary hydrodynamic yield = 21.7 ± 0.8 Kt

*Reiterated solution.

CHAPTER 8

OPERATIONS TRINITY, BIKINI-ABLE, AND SANDSTONE

By F. B. Porzel and D. F. Seacord, Jr.

Dec. 15, 1953

8.1 GENERAL

This report is the last in a series summarizing the first fireball analyses with the analytic solution for the hydrodynamic yields of nuclear weapons of past operations.

With the exception of Bikini-Baker and Jangle-Underground, all test detonations conducted by LASL and UCRL have now been investigated in terms of the hydrodynamic yield. Many of the results have been termed "preliminary" in the sense that certain improvements can be made, but no data have been reanalyzed, and the calculating methods will probably change over a period of time; minor variations in the yield figure may be expected when the preliminary studies are completed and a standardized procedure is adopted. In all probability the earlier shots (such as Trinity, Bikini, and Sandstone) will not be studied further in view of the basic uncertainties in the raw data, which cannot be improved by further study.

The camera coverage of fireball growth is meager in the light of present standards; furthermore, the uncertainty in zero time precludes an improvement in the yield as a result of time corrections.

8.2 TRINITY

The basic data were obtained from the radius-time plot of individual data points in Volume 24 of Report LA-1025. Three 8-mm and 16-mm Fastax cameras recorded fireball growth, and two Mitchells recorded shock growth after breakaway; although the number of cameras involved was not as large as would be desired, the time spread covered was exceptional (out to about 400 msec).

The best time resolution is quoted at ~0.1 msec, and the time scales of all other cameras were fitted to the slow (655 frames/sec) 16-mm Fastax. Zero time is not independently known relative to the nuclear explosion but was determined by extrapolation of $R \sim t^{0.4}$. In view of these uncertainties early time data must be regarded as ambiguous.

The technique used to measure the fireball and shock diameters is not known, but from discussions of measurements in Report LA-1025 the Mach region was avoided when measuring shock growth. By present hydrodynamic considerations, the Mach stem should close near the end of the measurement.

A "light curtain" was observed rising over the fireball surface; a possible explanation for this phenomenon is a reinforcement by radiative transport.

The yield obtained by considering only those data points up to breakaway (at ~16 msec) is 26.9 Kt; considering shock-front data beyond breakaway in addition to fireball data, a yield of 27.2 Kt is indicated. A further confirmation of a yield on the order of 27 Kt is obtained from pressure-distance measurements. A scaling of the IBM Problem M pressure-distance curve (with a reflection factor of 2) to 27 Kt shows remarkable agreement with pressures measured close to the ground, i.e., in the Mach region. Furthermore, pressures derived from the reiterated analytic solution also show excellent agreement with the IBM Problem M free-air curve at 27 Kt; values from the nonreiterated solution show some scatter. This similarity scaling to the IBM free-air curve indicates the same fluctuation in yield as those obtained with the unreiterated analytic solution. This is evidence that the perturbations are not the result of the analytic solution but are due to uncertainties in the initial data.

It is of interest to note the agreement between the Trinity free-air pressure-distance curve and the theoretical curves from IBM Problem M. Although the full use of the IBM run has become possible only during the past year or so through work done in Group J-10 in evaluating its energy as 11.5 Kt instead of previous values from 10 to 13.5, it is a fair statement that the free-air curve for atomic bombs was known theoretically and had actually been confirmed experimentally on the first atomic bomb ever fired. In the subsequent operations of Bikini and Sandstone, the low-pressure measurements were used to establish efficiencies like 90 per cent for nuclear explosions relative to TNT, discrediting both the Trinity data and IBM Problem M. On Greenhouse this efficiency was reduced to numbers on the order of 60 per cent, and on Operations Tumbler through Ivy the efficiency was again lowered to values on the order of 40 per cent, both from NOL rocket-trail studies and from the work by Group J-10 on a theoretical basis, fireball analysis, and mass motion. In eight years then the "data" have come full circle back to the original findings on Trinity. The point here is that the low pressures observed on Buster in the region of practical military interest, in comparison with Report LA-743R and subsequent papers, were due in good part to high free-air curves which, for rigor, had used the data of Bikini, Sandstone, and Greenhouse rather than the theory or data of Trinity.

The yield value of 27.2 Kt is in substantial disagreement with the "average" radiochemistry value of ~20.5 Kt and indicates that both Nagasaki and Bikini-Able may have been of higher yields than heretofore believed.

8.3 BIKINI-ABLE

Owing to timing-signal difficulties the fireball photographic program obtained no data on fireball growth; however, one radius-time curve was obtained by Brian O'Brien with a high-speed streak camera. Original tabulated data were not available, and the starting point for the analytic solution was a radius-time plot in Report LAMS-438.

An inherent uncertainty in a high-speed streak-camera record of this type is the lack of knowledge of breakaway time. A streak camera is inherently incapable of distinguishing breakaway by an inspection of the image, as is afforded by the complete image in the usual fireball photograph. Furthermore, the short exposures and decreasing illumination combine to produce an image smaller than the true image. Therefore early time data have been stressed rather than late times as is usually the case.

With a single uncertain film the derived yield is merely an estimate and should not be considered as accurate as the usual analytic-solution yields.

The Bikini-Able yield of ~25 Kt is, like Trinity, appreciably higher than previously reported yields.

8.4 SANDSTONE X-RAY, YOKE, AND ZEBRA

The original data R-t curves were obtained and were the basis for the analytic solution. Again, yields have not been achieved to the accuracy of those of later operations when the fireball photographic program was considerably extended and improved.

There is probably little interest in Sandstone at this late date, but the shots were investigated for logical completeness in the hydrodynamic yield series and to establish whether serious discrepancies might exist between the analytic solution and other yield methods. No serious discrepancies were found. The hydrodynamic yields for the three detonations are: X-ray, 36 ± 4 Kt; Yoke, 50 ± 5 Kt; and Zebra, 20 ± 2 Kt.

X-ray is in excellent agreement with radiochemistry (36.5 Kt) and with fireball scaling (36.5). Yoke and Zebra are somewhat higher than the radiochemistry values of 48.7 and 18.2, respectively. The basic uncertainty in data may be of this order of magnitude, and these discrepancies are not considered significant.

Historically, all fireball data prior to Ranger should be regarded with some suspicion because at the time there was such a strong disposition to expect the slope n to be 0.4. There was a natural tendency to correlate data on this basis, either to estimate zero times or in making fits with $R^{5/2}$ vs t plots. The disagreement of the Sandstone data with n = 0.4 was well known, but the slope was still regarded as constant, on the order of 0.375. In Report[1] LA-1214, which was issued at the beginning of Ranger, these serious anomalies were resolved, the slope was shown to be a variable, and the data were so recognized thereafter. As a consequence, much more assurance would be felt if the pre-Ranger data were now measured again from basic data and were correlated on the basis of a variable slope, instead of a constant value, let alone one of 0.4.

REFERENCES

1. F. B. Porzel, Rate of Growth of Atomic Fireballs, Los Alamos Scientific Laboratory, Report LA-1214, February 1951.
2. Hans A. Bethe and Karl Fuchs, Measurement of Nuclear Bomb Efficiency by Observation of the Ball-of-Fire at Early Stages, Los Alamos Scientific Laboratory, Report LA-516, February 1946.
3. J. O. Hirschfelder and J. L. Magee, A Critical Summary of Some Able Shot Measurements, Los Alamos Scientific Laboratory, Report LAMS-438, Sept. 1, 1946.
4. R. A. Houghten, Space-Time Relations Measured from Sandstone Photography, Sandstone Report, Annex 7, Pt. 2, September 1950.

[redacted]

Table 8.1—FIREBALL YIELD, TRINITY*

Analytic Solution

Data: Films from:
- 8-mm 7110 frames/sec Fastax
- 16-mm 3560 frames/sec Fastax
- 16-mm 655 frames/sec Fastax
- 35-mm 107 frames/sec Mitchell
- 35-mm 119 frames/sec Mitchell

Ambient conditions:
- Pressure (P_0), 0.854 bar
- Density (ρ_0), 1.006 g/liter
- Sound velocity (C_0), 0.345 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.500	28.0	65.9	5400	0.164	22.1	2.25	25.7
0.707	32.2	53.3	3500	0.162	22.3	2.31	26.3
1.000	37.1	43.0	2300	0.160	22.3	2.36	26.5
1.414	42.5	34.5	1500	0.156	22.2	2.39	26.0
2.000	48.7	27.6	980	0.152	22.0	2.48	26.2
2.828	55.8	22.2	625	0.150	21.6	2.59	26.4
4.000	63.8	17.9	410	0.150	21.1	2.65	26.5
5.657	73.0	14.6	270	0.151	20.7	2.74	27.1
8.000	83.6	12.0	180	0.155	20.4	2.79	27.8
11.314	96.1	9.9	122	0.162	20.4	2.79	28.9
16.000	110.4	8.2	82	0.168	20.6	2.67	29.0
22.628	127.5	6.8	56	0.174	21.1	2.59	29.8
32.000	147.6	5.7	39	0.182	21.9	2.46	30.8
45.248	171.2	4.7	27	0.186	23.0	2.20	29.5
64.000	198.8	3.9	18	0.188	24.3	1.96	28.1
90.496	231.1	3.2	12	0.189	25.7	1.76	26.9
128.00	268.9	2.7	8.3	0.194	27.5	1.57	26.4
180.99	313.8	2.3	5.9	0.205	29.7	1.38	26.2
256.00	368.1	2.0	4.3	0.221	33.0	1.12	25.6
361.98	434.1	1.7	3.1	0.235	37.6	0.87	24.3
					Av. (statistics only)		27.2 ± 0.4

Recommended hydrodynamic yield = 27.2 ± 2.7 Kt

* Reiterated solution. Shock-front data beyond breakaway utilized after 16 msec. Original fireball yield[2] = 25.0 ± 2.5 Kt.

[redacted]

Table 8.2—FIREBALL YIELD, BIKINI-ABLE*

Analytic Solution

Data: O'Brien streak camera

Ambient conditions:
Pressure (P_0), 0.994 bar
Density (ρ_0), 1.153 g/liter
Sound velocity (C_0), 0.347 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.1768	18.4	124.5	19500	0.173	21.4	1.81	24.1
0.2500	21.2	99.4	12500	0.166	21.9	1.91	25.0
0.3536	24.4	79.9	7900	0.162	22.0	2.06	26.4
0.500	28.0	64.1	5100	0.158	22.0	2.13	26.7
0.707	32.1	51.1	3250	0.152	21.8	2.09	25.0
1.000	36.7	40.4	2050	0.146	21.3	2.10	23.4

Av. (statistics only) 25.1 ± 0.5

Recommended hydrodynamic yield = 25 ± 5 Kt

* Only one record obtained on fireball growth. Fireball by similarity scaling[3] = 21.3 Kt.

Table 8.3—FIREBALL YIELD, SANDSTONE-X-RAY*

Analytic Solution

Data: Five Fastax films

Ambient conditions:
Pressure (P_0), 1.012 bar
Density (ρ_0), 1.175 g/liter
Sound velocity (C_0), 0.347 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.500	31.6	66.4	5450	0.133	40.1	1.97	38.5
0.707	35.8	53.3	3550	0.133	37.7	2.08	38.5
1.000	40.7	42.8	2280	0.134	35.5	2.16	37.6
1.414	46.1	34.4	1500	0.134	33.5	2.29	37.6
2.000	52.4	27.8	960	0.135	31.6	2.44	38.2
2.828	59.5	22.5	635	0.137	29.9	2.49	37.5
4.000	67.7	18.1	415	0.138	28.5	2.51	36.2
5.657	77.1	14.7	272	0.139	27.1	2.51	34.5
8.000	87.7	11.8	175	0.140	25.9	2.41	32.1
11.314	100.0	9.6	113	0.141	24.8	2.36	30.4

Av. (statistics only) 36.1 ± 0.9

Recommended hydrodynamic yield = 36 ± 4.0 Kt

* Solution based on original-data plot from five Fastax films. Fireball by similarity scaling[4] = 36.5 Kt.

Table 8.4 — FIREBALL YIELD, SANDSTONE-YOKE*

Analytic Solution

Data: Seven Fastax films

Ambient conditions:
Pressure (P_0), 1.009 bar
Density (ρ_0), 1.175 g/liter
Sound velocity (C_0), 0.347 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
1.000	42.4	45.6	2600	0.139	43.7	2.16	48.2
1.414	48.2	36.5	1680	0.138	41.7	2.27	48.0
2.000	54.9	29.4	1100	0.138	39.7	2.41	48.7
2.828	62.4	23.7	710	0.139	37.8	2.56	49.6
4.000	71.1	19.3	475	0.142	36.2	2.65	50.1
5.657	81.1	15.7	315	0.145	34.9	2.75	51.3
8.000	92.6	13.0	213	0.151	34.0	2.81	53.1
11.314	106.2	10.7	142	0.156	33.6	2.73	52.6

Av. (statistics only) 50.2 ± 0.7

Recommended hydrodynamic yield = 50 ± 5 Kt

* Reiterated solution. Solution based on original-data plot from seven Fastax films. Fireball by similarity scaling[4] = 45.6 Kt.

Table 8.5 — FIREBALL YIELD, SANDSTONE-ZEBRA*

Analytic Solution

Data: Three Fastax films

Ambient conditions:
Pressure (P_0), 1.008 bar
Density (ρ_0), 1.168 g/liter
Sound velocity (C_0), 0.347 meter/msec

Time (t), msec	Radius (R), meters	Shock velocity $\left(\frac{U}{C_0}\right)$	Pressure $\left(\frac{P}{P_0}\right)$	Slope (n^2)	ϕ^5 $\left(\frac{R^5}{t^2}\right)$	Factor (F)	Yield (W), Kt
0.500	27.7	61.2	4650	0.146	21.0	2.00	22.4
0.707	31.6	48.3	2920	0.141	20.2	2.05	21.2
1.000	36.0	38.7	1880	0.140	19.3	2.22	21.8
1.414	40.9	31.1	1240	0.139	18.4	2.35	21.9
2.000	46.6	25.0	780	0.138	17.5	2.43	21.5
2.828	53.0	20.1	510	0.138	16.7	2.41	20.2
4.000	60.3	16.1	330	0.138	15.9	2.45	19.6
5.657	68.6	13.0	210	0.138	15.1	2.42	18.4
8.000	78.0	10.5	135	0.139	14.4	2.32	17.0

Av. (statistics only) 20.4 ± 0.6

Recommended hydrodynamic yield = 20 ± 2 Kt

* Solution based on original-data plot from three Fastax films. Fireball by similarity scaling[4] = 17.9 Kt.

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